CANADA

INCENDIARY EFFECTS OF NUCLEAR WEAPONS

A CRITICAL REVIEW AND GUIDE

EMO MANUAL No. 7

EMERGENCY MEASURES ORGANIZATION

OTTAWA

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INCENDIARY EFFECTS OF NUCLEAR WEAPONS

A critical review and guide

Prepared for the

EMERGENCY MEASURE ORGANIZATION

In consultation with the

DEFENCE RESEARCH BOARD

by

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SECTION 1

INTRODUCTION

1.1 In time of war, it is likely that extensive fires may result from the detonation of nuclear weapons at urban targets. The prime intention of this manual is to correlate available data on the incendiary effects of these weapons in such a manner that an estimate of the resulting property losses may be made. Apart from the total energy yield of a nuclear weapon and the height at which it is detonated, it will be shown that the production of fires resulting from the emission of radiant energy depends on atmospheric conditions, local geography and the presence of easily ignited combustibles such as paper.

1.2 To obtain an estimate of the size of the zones in which fires are likely to occur, many assumptions must necessarily be made. Two of these are of fundamental importance. The first is that ignitions caused by radiant heat emitted from weapons define the boundary of these zones and that fires caused by stoves overturned by blast, by electrical short-circuits and the like, occur only sporadically beyond this boundary. In other words, fires resulting indirectly from blast effects are considered to be of less importance than those attributable to thermal emission. The second assumption is that the risk of major blazes resulting from the sustained flaming ignition of light, solid, fuels existing inside of building is high. This implies that substantial losses are expected to result from the growth of fires from minor ignitions. Due to the assumptions that must be made and the uncertainties inherent in dealing with nuclear weapons, the related natural phenomena and ignition itself, it must be borne firmly in mind that the method of determining sizes of fires zones given in the manual is not precise. Nevertheless, it is believed to be sufficiently accurate for planning purposes.

1.3. It is certainly true that much of the ignition information that was widely believed to be valid as recently as 1962 is now thought to be unrealistic. While the data presented here are believed to be the best available at the time of writing, it is entirely possible that new research information may show them to be inaccurate or incomplete. However, most of the work that has been used as source material has been conducted with skill and care and it is hoped that subsequent necessary changes may be of a relatively minor character.

SECTION 2

FIRE AS A WEAPON OF WAR

2.1 The greatest destructive effects of fire, when used as a weapon of war against cities, are achieved when fire-fighting resources are overwhelmed by the number, distribution and rate of production of ignitions. The success of an attack depends on minor blazes remaining unattended and uncontrolled until they have grown to major proportions and involve substantial city areas. The amount of destruction depends greatly on the length of time in which control is lost.

2.2 Assault by fire has a long history. Launched against cities with high building densities, it has often been markedly successful. However, with the introduction of highly organized fire-protection systems, comparable results may only be achieved by greatly increasing the rate and scale on which an attack must be mounted. It is probably safe to say that the provisions made to reduce a city by fire a century ago are not likely to be adequate now. Some of the most recent examples of massive fire attacks occurred during World War II in the aerial bombardment of Hamburg, Dresden, Kassel, Tokyo and Hiroshima. The property losses suffered in these cities are accounted among the greatest inflicted during the course of that war. In each case, the attacks were delivered swiftly and on such a scale that the fighting of more than a small proportion of the blazes was prevented. Control was quickly lost and was not regained until the destruction of property was enormous.

2.3 It will be noticed that of these only one, Hiroshima, was attacked with a nuclear weapon. As Hiroshima suffered less fire damage than Hamburg, and Nagaski, the second target to undergo nuclear attack, suffered less than either, it is not necessarily reasonable to assume that nuclear weapons produce more fire destruction than conventional weapons. However, since 1945 the energy yield of nuclear weapons has tended greatly to increase, and it may be anticipated that the size of the area likely to be affected by heat from these weapons will also increase.

2.4 Despite the fact that, due to its economy in aircraft or missiles, a nuclear attack is much simpler to mount than an air raid employing conventional incendiary weapons, there are many advantages that the latter has which the former does not possess. For example, the conventional weapon attack may be delivered in a uniform or in some other chosen pattern of weapon density. By its nature, a nuclear weapon's thermal effects cannot be distributed in a uniform or selective manner, but, instead, it tends to waste energy in a needless over-destruction of property near the detonation point. Also, the zone of damage produced by conventional weapons is not as greatly dependant

on weather and topographical conditions as that caused by nuclear weapons. Furthermore, conventional weapons tend to be more efficient in igniting a wide range of combustible fuels than nuclear weapons. Nevertheless, a high energy yield nuclear weapon is capable of starting fires over many square miles of a city and it does not now appear likely that comparable results may be achieved by air raids of the type that were mounted during World War II.

2.5 The discussion that follows will attempt to provide methods of assessing the property damage that may result from fires caused in a nuclear attack on a city. Most of the information presented will be taken from many reports on nuclear weapon effects and from experience and experimental work on fires. Although little will be said of blast effects and nuclear radiations, it is not intended to infer that fire damage is of greater importance. Instead, it is hoped that the discussion will help to place fire damage in its proper context with blast and nuclear radiation effects.

SECTION 3

THERMAL EMISSION FROM THE NUCLEAR WEAPON

3.1 When a nuclear weapon is detonated, approximately 80 percent of the released energy is in the form of X-rays and ultra-violet rays that are quickly absorbed within a short distance in the surrounding air. Most of the remaining energy is emitted as nuclear radiations; that is, as neutrons, alpha and beta particles, and gamma rays. As this latter portion plays no part in the production of ignitions, its effect will be ignored in the following discussion.

3.2 A high proportion of the absorbed radiant energy serves to excite the atoms and molecules of atmospheric oxygen and nitrogen. Some is imparted as kinetic energy; the remainder is stored in the form of internal atomic or molecular energy. The distance within which the energy is yielded depends on the density of the air, and, therefore, upon the altitude of the detonation point. Near sea level, absorption occurs within a few feet of the weapon, while, at an altitude of about 30 miles, the corresponding distance is several thousand feet.

3.3 As the total energy yield of a 1 kiloton weapon is approximately 10^{12} calories, and as the evolution of the X-rays and ultra-violet rays occurs almost instantaneously upon detonation, it is easy to see that the effect on the absorption area is extremely violent. The shocked air attains a very high temperature and seeks to de-energize itself and return to equilibrium conditions by imparting excess energy to the surrounding air, which, in turn, is thereby rendered into an approximately uniformly hot state. At this early stage of the development of what is usually referred to as a fireball, the energy emitted from the surface of the expanding sphere of hot air is associated with electro-magnetic waves of very short wave-lengths and very short ranges in air. These waves are principally "soft" X-rays that serve to shock and heat still more air in front of the sphere.

3.4 In order to discuss the events that follow the earliest conditions prevailing in the creation of a fireball, it is necessary to make a distinction between weapons detonated at heights of less than, roughly, 100,000 feet and those detonated at higher altitudes. This is due to marked differences in thermal emission characteristics that are attributable to the decrease of air density as the height above earth increases. To preserve continuity, it is not proposed to contrast these differences at this stage of the discussion. However, it should be noted that the altitude of 100,000 feet does not represent a sharply defined, critical, height at which the nature of the emission changes abruptly, but, rather, an arbitrarily chosen height lying in the middle of a transition from one set of

fireball characteristics to another, quite different, set. It is very important to bear in mind that the description that ensues applies primarily to weapons detonated below 100,000 feet. The discussion of higher altitude bursts will be deferred to Appendix A.

3.5 When the fireball temperature of weapons detonated below 100,000 feet decreases to approximately 300,000°C, a shock front, that forms in the heated air, emerges from the fireball and advances at high speed before it. This front heats and compresses the air which it encounters in its outwards progress from the detonation point. There are two phenomena associated with the shock pulse that have a strong and rather curious effect on the heat emission of a nuclear weapon. The first is that the violence of the shock produces small, but significant, quantities of ozone, nitrogen dioxide and other substances that have a high capacity for absorbing shortwave electro-magnetic radiations from the hot surface of the fireball. The result is that although the temperature at shock separation is approximately 300,000°C, the apparent surface temperature of the fireball, as recorded by an observer some distance away, is considerably lower. As the front advances, the true surface temperature decreases: but, this decrease is associated with radiations of longer wave-lengths that are less easily absorbed in the atmosphere so that, quite anomalously, the surface temperature appears to an observer to be rising. Having reached a maximum, the apparent temperature then decreases until the apparent and true shock front temperatures coincide at approximately 1,800°C. During this trend, the pulse velocity and the true shock front temperature are both decreasing so that the potential to produce strong absorbers, like ozone and nitrogen dioxide, is correspondingly decreased. At the same time, a substantial part of the electro-magnetic radiations associated with a relatively cool fireball surface consists of highly penetrating visible light and infra-red rays that are not greatly affected by these atmospheric absorbers.

3.6 The second phenomenon is associated with the effect of the shock front upon the hotter core of the fireball about which it forms a shell. Due to the difference in temperature, the wave-lengths of the radiations associated with the core are consistently shorter than those of the shock front. This results in the frontal, compressed air, behaving as a good absorber of the energy emitted from within the fireball. Thus, to an observer, the hot core appears to be obscured by an "opaque" outer cover. This condition prevails until the decreasing temperature at the shock front approaches 1,800°C., when the core is gradually revealed. This results in a second increase in the apparent fireball surface temperature as recorded by the observer. At this stage, the true surface temperature of the revealed core is roughly in the range of 7,500°C to 8,000°C. This is consistent with a spectrum of electro-magnetic rays lying in the ultra-violet, visible light and infra-red wave bands, none of

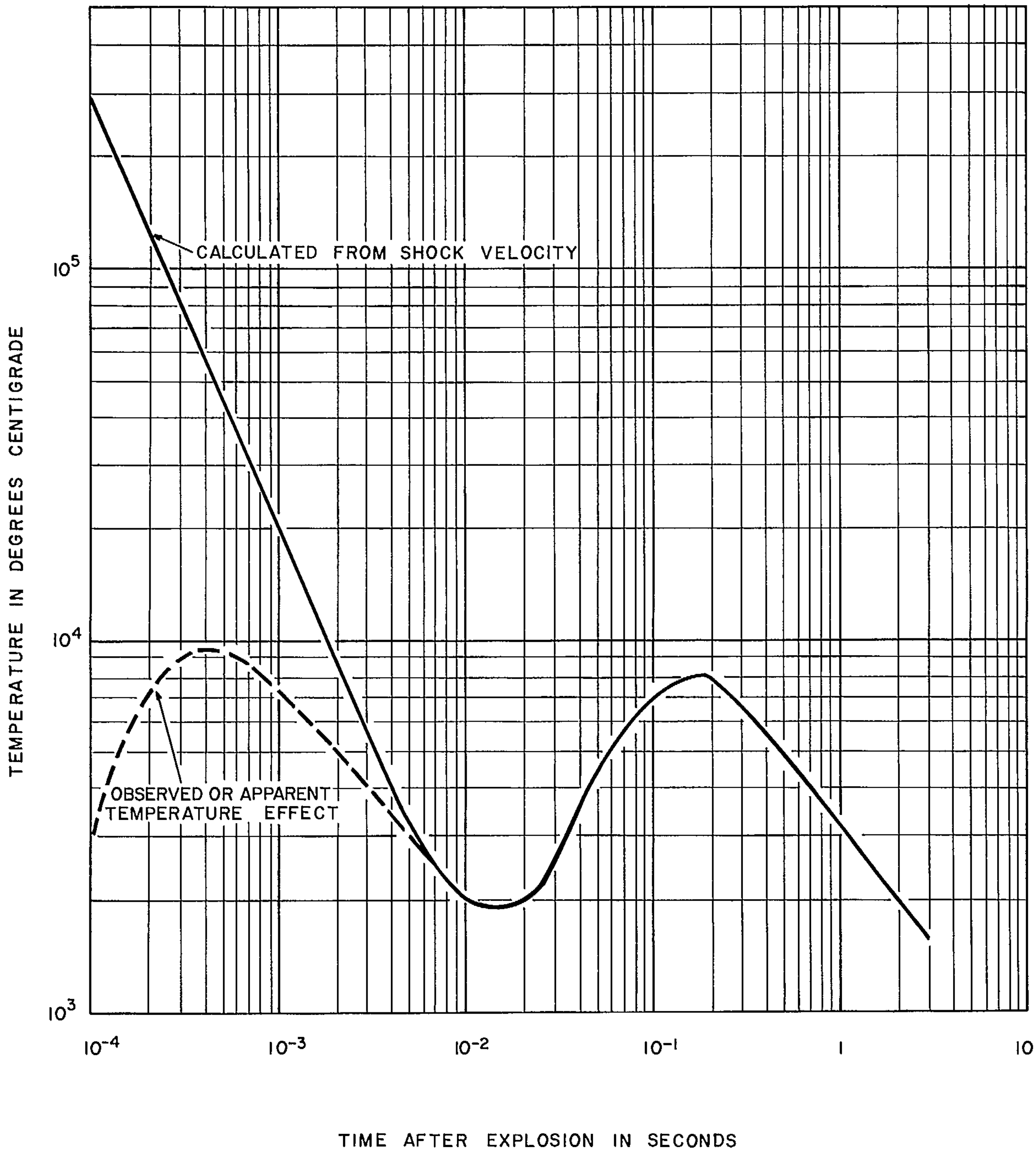


FIG. 3.7.1 VARIATION OF FIREBALL SURFACE TEMPERATURE WITH TIME FOR A 20 KILOTON TOTAL ENERGY YIELD WEAPON

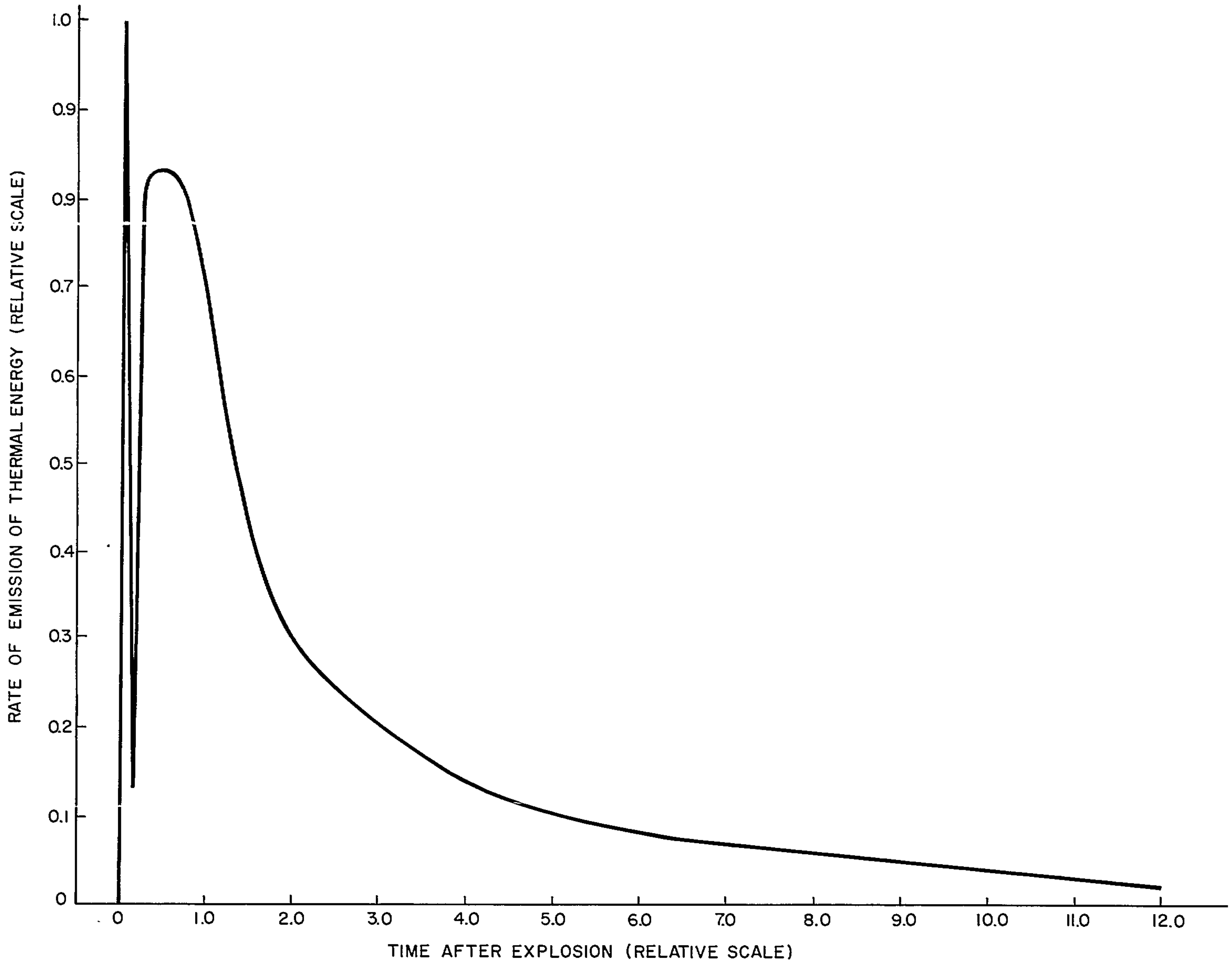


FIG. 3.8.1 EMISSION OF THERMAL RADIATION IN TWO PULSES (AIR BURSTS).

which is as readily absorbed as "soft" X-rays. Therefore, it may be expected that the apparent fireball surface temperature will rise from 1,800^{o}C to the true temperature of approximately 7,500^{o}C. to 8,000^{o}C. and, with the passage of time, decrease slowly as the fireball cools.

3.7 These two phenomena are shown in graphical form on Figure 3.7.1. It is important to note that although the apparent fireball temperature, as recorded by the observer, does not give a true value in the early stages after detonation, nevertheless, it always gives a true indication of the heat actually received at the observer's position. Of course, this delivered quantity is of the greatest interest in the production of fires. From the figure, it may be seen that the first temperature pulse is of much shorter duration than the second, in which true temperatures are recorded.

3.8 While the foregoing account of the history of fireball surface temperatures is a useful guide in a qualitative description, it is not very convenient for a discussion of the thermal emission and the resulting fires. For this purpose, it is more useful to consider the thermal energy and the corresponding power delivered to a point in the target area. Compatible with the two fireball surface temperature pulses shown in Figure 3.7.1, it may be concluded that the thermal energy delivery will also consist of two pulses, and that there will be two delivered power maxima. This is shown on Figure 3.8.1. Due to its brevity, the first pulse may be ignored without significant error and attention may be confined to the second pulse. Thus, in the following discussion, the delivered heat will be assumed to consist only of that contained in the second pulse.

3.9 Approximate mathematical relationships may be established to describe the thermal power and total heat deliveries at a selected point in the target. These may be obtained from experimental data and by fitting simple curves of known shape against the second power pulse in Figure 3.8.1. The fire-producing heat yield of a nuclear weapon has been estimated to be approximately one-third of the total energy released upon detonation. At first sight this may not appear to be consistent with the 80 percent yield mentioned in Section 3.1. However, the greater part of this latter energy is converted to shock and blast, leaving only a lesser part available as heat. Eventually, of course, substantially all of the weapon energy is degraded to heat but the time elapsed is so long that only that part which is emitted from the fireball surface is important in the production of fires. If this heat is assumed to be delivered from a point source, through a vacuum, to a target, the heat delivered per unit area may be expressed in the form of Equation 3.9.1. The corresponding thermal power delivery may be represented in the form of Equation 3.9.2. Both of these relations are only fair approximations and they should not be regarded as precise.

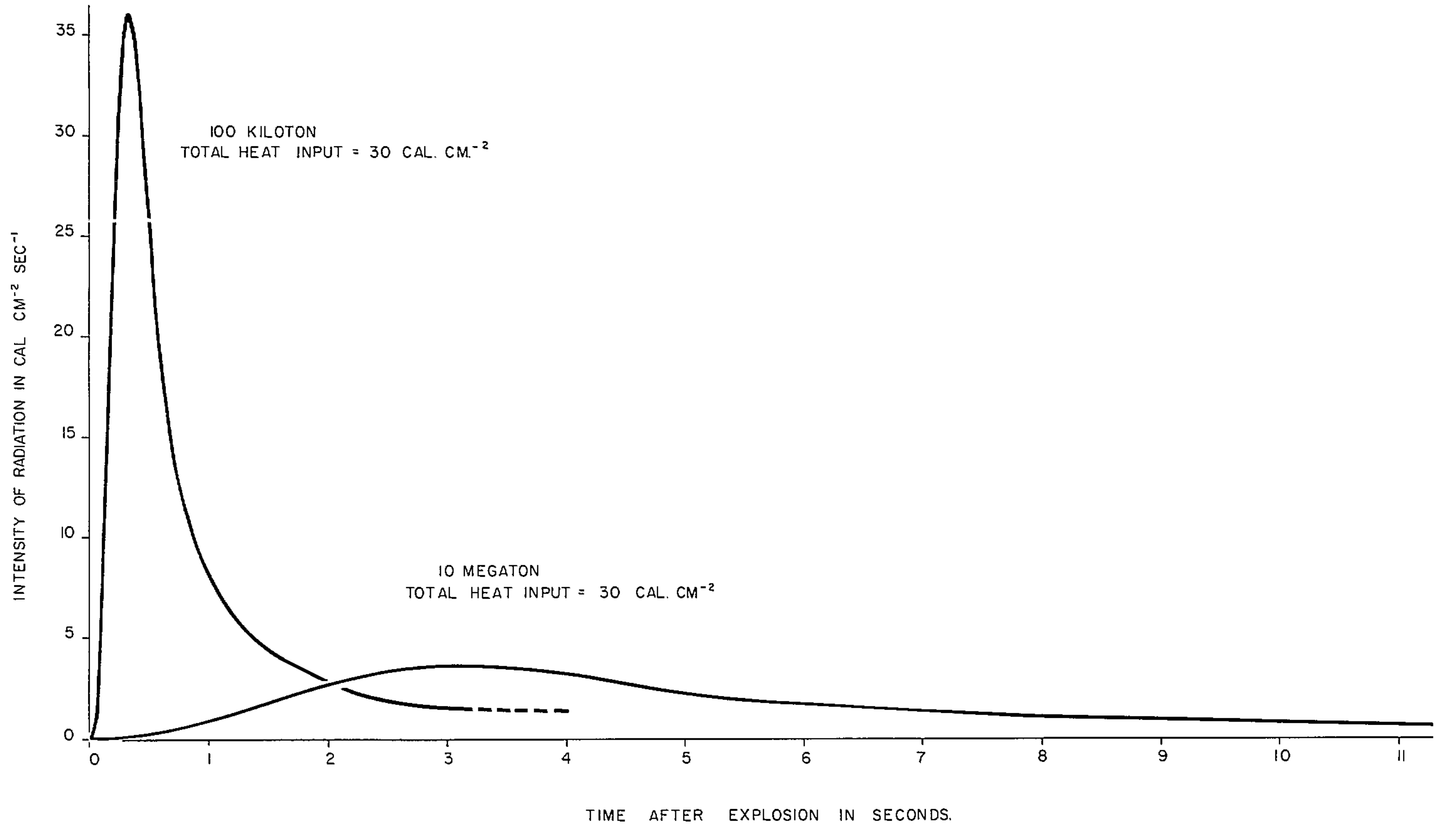


FIG. 3.9.1. GRAPH OF HEAT INTENSITY vs TIME FOR 10 MEGATON & 100 KILOTON TOTAL ENERGY YIELDS

$$Q = \frac{W}{4.51} \times \frac{10^8}{R^2} \qquad - 3.9.1$$

$$P = \frac{2 \times 10^{14}}{WR^2} \times t^3 \times e^{\frac{-93.75t}{\sqrt{W}}} \qquad - 3.9.2$$

where Q	=	total heat delivered in calories x cm^{-2}
P	=	thermal power delivery in calories x cm^{-2} x sec^{-1}
W	=	total weapon energy yield in kilotons
t	=	time after detonation in seconds
R	=	distance from detonation point to selected location in target in feet.

It is interesting to plot power curves for varying weapon sizes and to compare their forms. In Figure 3.9.1 graphs of power (or, expressed in equivalent terms, intensity, irradiance or flux) against time are shown for two weapons, one of 100 kilotons total energy yield, the other of 10 megatons total energy yield. In each case the heat delivered has been arbitrarily chosen to be 30 calories per square centimeter. From an inspection of the graphs, it is quite apparent that the former weapon delivers the greater part of its heat more quickly than the latter and that the peak intensities are therefore markedly different. This illustrates one of the most important effects of weapon energy upon heat delivery. It will be shown in Section 7 how this affects ignition.

3.10 The time after detonation at which peak power is attained is an important invariant characteristic of a weapon. The approximate relation between this time and total weapon energy yield is given in Equation 3.10.1. The corresponding approximate peak thermal intensity

$$t_p = 0.032 \times \sqrt{W} \qquad - 3.10.1$$

where t_p	=	time after detonation at which peak thermal intensity is attained in seconds
W	=	total weapon energy in kilotons

is given in Equation 3.10.2. As the expressions in Equations 3.9.1, 3.9.2, 3.10.1 and 3.10.2 are all approximations it should not be expected that they may be perfectly correlated.

$$P_p = 3.4 \times 10^8 \times \frac{\sqrt{W}}{R^2} \qquad - 3.10.2$$

where P_p = peak thermal intensity, in calories x cm^{-2} x sec^{-1}

W = total weapon energy yield in kilotons

R = distance from detonation point to selected location in target, in feet.

If they were a mathematically perfect set, then it should be possible to show that $\int_0^\infty Pdt = Q$. If this integration is performed it may be seen that the left hand side is approximately 40 percent less than the right hand side of the expression. This should not be viewed as a serious fault, for the greater part of the error accrues after most of the energy has been delivered and the period of greatest interest for ignitions is past.

3.11 It must be emphasized that Equations 3.9.1; 3.9.2; and 3.10.2 (but not Equation 3.10.1) are valid only in a theoretical condition where the medium through which heat is delivered is a vaccum. As this has no practical application it is necessary to qualify these expressions and render them into a state where they may portray thermal transmission through realistic atmospheres. This will be performed in the ensuing sections.

3.12 Before leaving a discussion of heat delivery, it is worthwhile to draw attention to the distance term, R^2, in the denominator of Equations 3.9.1; 3.9.2; and 3.10.2. The inclusion of this term may be explained by imagining the surface of a sphere, of radius R, placed such that a point-source heat emitter is located at its centre. In a perfectly uniform atmosphere the heat impinging upon this surface is uniform over the whole area. As all electro-magnetic waves travel through a vacuum with the velocity of light, the power emitted from the source at any given instant is substantially equal to the power arriving at the surface at that same instant. If the power at the source and at the surface are P_O and P_R respectively then $P_O = 4\pi R^2 P_R$, in any compatible set of units of measurement. In other words, P_R is inversely proportional to the square of the distance from the source to the receiver. This is the basis of the remark made in Section 2.4, that a nuclear weapon is not an efficient incendiary device due to its inability to deliver heat uniformly to a target.

SECTION 4

ATMOSPHERIC EFFECTS ON THE TRANSMISSION OF THERMAL RADIATION

4.1 In a vacuum, radiant heat travels in substantially straight lines from an emitter to a target. The power and energy equations in Sections 3.9 and 3.10 were based on this idealized condition. Under practical conditions, where heat travels through a real atmosphere, the equations are no longer valid. This failure is due to a considerable portion of the radiation ceasing to follow continuous straight-line paths, and, partly, due to losses of heat to atmospheric gases.

4.2 It has been determined that the wave-lengths of the electro-magnetic energy emitted during the second, major, thermal pulse lie approximately in the range between 0.3 microns and 3.6 microns. This corresponds to heat in infra-red , visible light and ultra-violet wave bands. Of these, the last is of little importance in producing the ignition of combustibles.

4.3 It is known that each wave-length has its own characteristic properties. As there is an infinite number of wave-lengths in any finite range, such as that under discussion, it is obviously impossible to study each. Therefore, the usual method employed is to divide the range into a convenient number of wavebands. After investigating each band the properties are aggregated to provide a complete picture. Naturally, the accuracy of this method depends on the number of waveband divisions studied.

4.4 In particular, it is known that some wave-lengths in the energy spectrum of the heat emitted from the fireball have high absorption characteristics in atmospheric gases. Also, some have a characteristic ability to be scattered from airborne particles. The degree to which absorption and scattering take place varies greatly from one wavelength, or waveband, to another. For example, atmospheric carbon dioxide and water vapour tend to absorb some infra-red radiations quite readily. Of the two, carbon dioxide is the less effective. On the other hand, both are much less effective in absorbing radiations in the visible light spectrum of energy. While it is not proposed to deal exhaustively with these characteristics, it should be noted that absorption is not merely a function of wave-length but also of the amount of absorber present. For example, the amount of water vapour in air is subject to wide variation. Thus, it may be expected that absorption will vary with the ambient relative humidity. On the other hand, the carbon dioxide content does not change appreciably and its capacity to absorb remains essentially constant. Fortunately, it is usually only necessary to specify either a wet or dry atmosphere to obtain a fair estimate of the total effect.

4.5 In real atmospheres, absorption has usually considerably less effect on heat transmission than scattering. This mechanism may be visualized as heat, that has impinged on an airborne particle and imparted some energy to it, being deflected from one straight-line course into a new course. It is very difficult to predict the number of deflection events and the resultant paths of any one ray, but, if the assumption is made that on a macroscopic scale of impingement the scattering is diffuse, then a fair estimate of its effects may be made. However, to do this it is necessary to combine experimental work with wave-length characteristics. The results appear to depend largely on the number and sizes of the airborne particles present and, possibly to a lesser extent, on their particle size distribution. Thus, over a city target where a number of chimney stacks are discharging soot into the air, the scattering is likely to be greater than that encountered in a rural area.

4.6 The effect of scattering upon a heat receiver in a target is two-fold. Some radiant heat that was originally directed in a straight line from a detonation point to the receiver is deflected and the thermal delivery is thereby reduced. By the same token, heat that was directed elsewhere may be turned from its original path to arrive at the receiver and enhance the direct ray thermal delivery.

4.7 There is yet another mechanism by which heat may arrive at a target. This is by the reflection of heat from the surface of the earth. While this is not truly an atmospheric effect on thermal transmission, it may be conveniently included with absorption and scattering to complete the description of contributory heat sources.

4.8 All naturally occurring materials absorb heat imperfectly. The degree of imperfection depends largely on the characteristics of the surface upon which the heat impinges. For example, a bright, shiny, surface tends to reflect more and absorb less heat than a dull, matt, surface. In the same sense, the surface of the earth tends to reflect heat in a manner prescribed by its surface cover. (e.g. Snow may be correctly assumed to act as a better reflector than pasture land or ploughed fields). The ratio of the heat reflected to that delivered, a pure number usually termed the surface albedo, provides a measure of absorption and reflection characteristics.

4.9 Due to the large variety of shapes and sizes of reflecting surfaces, it is almost impossible to provide meaningful estimates of the amount of reflected heat received at an arbitrarily chosen location in a built-up area. Surveys are usually difficult and expensive to conduct. Furthermore, if an assumed detonation point were badly selected, survey results are likely to be valueless. Often , the simplest approach is to assume that a target may be represented as lying on a diffusely reflect-

ing infinite Lambert plane of an albedo selected to represent a given ground cover. Under these conditions it is possible to make a mathematical analysis to determine the heat contributed by reflection at any given location.

4.10 By assuming an altitude of a detonation point, an atmospheric condition, an albedo for the target area and an essentially flat diffusely reflecting plane in and around the target area, it is possible to determine a numerical coefficient, τ_A. When the right hand sides of the energy and power relations in Equations 3.9.1; 3.9.2; and 3.10.2, which are valid for evacuated transmission media, are multiplied by this coefficient they are rendered into forms that make allowance for realistic atmospheric transmission effects. An adequate description of the mathematical process of determining τ_A is too lengthy to be presented here. However, Cahill, Gauvin and Johnson[1] have produced an excellent work on the subject in which they show that τ_A may be concisely expressed in the form of Equation 4.10.1. Furthermore, they give values of the coefficient for a variety of conditions. Some of these values are presented in Table 4.10.1, where the angle, ψ, is assumed to be zero.

$$\tau_A = \tau_{Abs} \times \tau_{SR} (1+G) (\cos\psi + \rho M) \qquad - 4.10.1$$

where τ_A = required numerical transmission coefficient, dimensionless

τ_{Abs} = a factor including effects of atmospheric absorption of heat, dimensionless

$\tau_{SR} (1+G) (\cos\psi + \rho M)$ = a factor including effects of diffuse scattering of heat from airborne particles and diffuse reflectance from a Lambert plane, dimensionless

G = enhancement factor due to diffuse scattering, dimensionless

ρ = albedo of target area, dimensionless

ρM = fraction of direct heat received as diffusely reflected heat from Lambert plane, dimensionless

ψ = angle between the direct heat ray and the normal to the reflecting surface.

LAND SURFACE	HEIGHT OF BURST in FEET	VISIBILITY in MILES	TRANSMISSION COEFFICIENTS τ_A HORIZONTAL RANGE IN FEET								
			0	10,000	20,000	30,000	40,000	50,000	60,000	70,000	80,000
Bare of snow	5,000	2	0.53	0.20	0.05	0.01					
Bare of snow	30,000	2	0.19	0.16	0.13	0.10	0.07	0.05	0.04	0.02	
Bare of snow	5,000	10	0.90	0.75	0.50	0.32	0.23	0.16	0.10	0.08	0.06
Bare of snow	30,000	10	0.64	0.58	0.54	0.48	0.44	0.38	0.34	0.29	
Snow covered	5,000	10	1.05	1.12	0.80	0.50	0.30	0.20	0.15	0.10	0.06
Snow covered	30,000	10	0.58	0.56	0.51	0.47	0.43	0.37	0.33	0.30	
Snow covered	5,000	50	1.05	1.40	1.40	1.25	1.06	0.92	0.78	0.68	0.63
Snow covered	30,000	50	0.78	0.73	0.68	0.63	0.60	0.57	0.54	0.52	0.49
Bare of snow	0	2	0.58	0.13	0.02	0.01					
Bare of snow	0	10	0.90	0.64	0.35	0.19	0.11	0.07	0.04		
Snow Covered	0	50	1.0	0.90	0.75	0.63	0.54	0.47	0.42	0.38	

Table 4.10.1 TRANSMISSION COEFFICIENTS, τ_A , FOR VARIOUS ATMOSPHERIC AND GROUND COVER CONDITIONS

4.11 Equations 3.9.1, 3.9.2 and 3.10.2 may now be rewritten respectively in the forms given in Equations 4.11.1, 4.11.2, and 4.11.3. Values of τ_A may be selected from Table 4.10.1.

$$Q = \tau_A \times \frac{W \times 10^8}{4.51 \times R^2} \qquad - 4.11.1$$

$$P = \tau_A \times \frac{2 \times 10^{14}}{WR^2} \times t^3 \times e^{\frac{-93.75t}{\sqrt{W}}} \qquad - 4.11.2$$

$$P_p = \tau_A \times 3.4 \times 10^8 \times \frac{\sqrt{W}}{R^2} \qquad - 4.11.3$$

where τ_A = coefficient given in Table 4.10.1

and other symbols are as given in Equations 3.9.1, 3.9.2 and 3.10.2.

4.12 Despite the fact that the basic energy and power equations now reflect more realistic atmospheric transmission conditions than those presented in Sections 3.9 and 3.10, they omit some important effects that are discussed in Section 5.

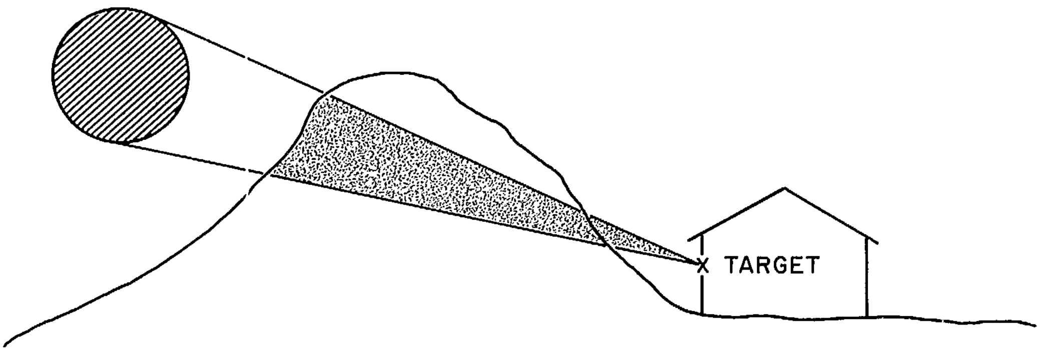


FIG. 5.2.1.a FIREBALL TOTALLY OBSCURED BY BARRIER.

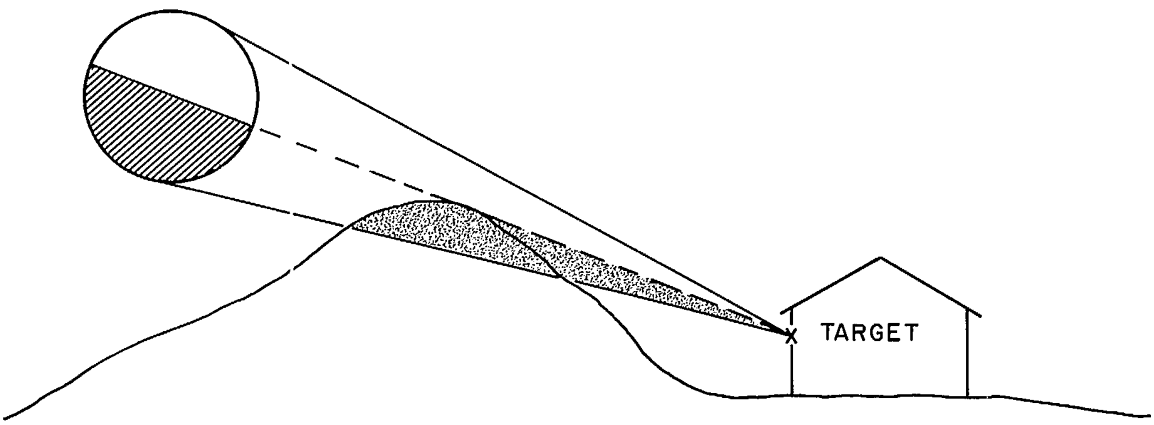


FIG. 5.2.1.b FIREBALL HALF OBSCURED BY BARRIER

SECTION 5

EFFECTS OF TOPOGRAPHY ON THE DELIVERY OF HEAT

5.1 In Section 4, the mechanisms affecting the transmission of heat through the atmosphere were discussed. For simplicity, a tacit assumption was made that no natural or artificial barriers existed between the source and any arbitrarily selected point in the target. As the heat from a nuclear weapon behaves very much like visible light (in fact, a substantial proportion of the thermal emission is visible light), it is obvious that even quite flimsy opaque screens may serve as effective thermal shields. Thus, the assumption may incur grossly conservative errors in targets where buildings, hills and trees may shield property from the full effects of a weapon.

5.2 For example, if it is supposed that a target lies in the lee of a hill, and that a weapon is detonated so that the fireball is obscured from view, then it may be concluded that no direct heat rays will reach the target. It is also probable that the heat delivered by scattering and ground reflection may also be diminished. If, on the other hand, one half of the fireball is visible from the target then it may be assumed that approximately one half of the available direct radiant heat will be delivered. These conditions are presented diagrammatically in Figure 5.2.1. Although the example of a hill obstruction has been used, the barrier may equally well be a wall, a building, trees, foliage or any other opaque material.

5.3 It may be argued that artificial barriers like buildings, and light natural barriers like trees, are valueless as they may be removed by blast effects. Such an argument may often be erroneous on two counts. The first is that blast may not be sufficiently strong to destroy the barriers completely . It is also possible that their collapse may take a sufficiently long period so that the integrity of the shielding is preserved during the delivery of a substantial amount of heat. The second is that the blast front may not arrive to damage the barriers until a significant part of the thermal pulse has been emitted. It is difficult to say which effect may be the more important. However, the latter is easily demonstrated . Figure 5.3.1 shows the times of arrival of blast fronts, at varying distances from ground zero, and the times of occurrence of peak thermal power (see Equation 3.10.1), after the detonation at 5,000 feet altitude of 100 kiloton, 1 megaton, 5 megaton and 10 megaton total energy yield weapons. It will be seen from the table that, as distance increases, the arrival of the blast front lags behind the time of attainment of peak thermal intensity by an increasing margin. This effect is most pronounced in weapons of smaller energy yield. The use of the table may be illustrated by the following example.

Example A building is located 10,000 feet from ground zero of a 1 megaton total energy yield weapon detonated at 5,000 feet. The building is surrounded by a dense wood of leafy trees. It is required to determine whether or not the wood is likely to provide thermal shielding for the house prior to the arrival of blast.

Solution Enter Table 5.3.1 under 10,000 feet at 1 megaton. The time of arrival of the blast front occurs at 5.5 seconds.
Enter Table 5.3.1 under "Time in seconds after detonation to peak thermal intensity".
The time is 1.0 second.
Therefore the peak thermal intensity occurs well in advance of the arrival of the blast front.
It is concluded that the trees are likely to provide substantial thermal shielding.

Answer

From this example, it may be seen that the protection afforded by such flimsy shields as leaves, is likely to be available for a sufficiently long period to have served as a useful barrier to heat that would otherwise have impinged on the building. The thermal effects on the leaves themselves are discussed in Section 11.

5.4 So far, the discussion has been limited to the "shadow" effect of external barriers. However, the argument may be extended to include the walls of buildings within which combustibles are present. For example, let it be assumed that paper is situated within a room of a house located some distance from the detonation point of a nuclear weapon. For the paper to receive direct radiant heat, there must be an unobscured line of sight between the paper and the fireball. This usually implies that there must be only a window between the heat source and the paper target and that there are no opaque partitions or walls to mask the view. Some possible variations on the amount of fireball that may be visible to the target are presented in Figure 5.4.1.

5.5 In Figure 5.4.1 (a) the whole fireball is visible through a window and the paper is subjected to all of the available direct radiant heat. In Figure 5.4.1 (b) only one quadrant of the fireball is visible, the remainder is obscured by an external wall. From this, it is reasonable to conclude that only one quarter of the available direct rays actually impinges on the paper. In Figure 5.4.1 (c) the fireball is much closer to the house. Nevertheless, only one half of it is visible from the target and, therefore, only one half of the available direct heat is delivered. In Figure 5.4.1 (d), the fireball is totally obscured from

TOTAL WEAPON ENERGY YIELD	TIME IN SECONDS AFTER DE-TONATION TO PEAK THERMAL INTENSITY	TIME OF ARRIVAL OF BLAST WAVE DISTANCE FROM GROUND ZERO, IN FEET							
		1,000	4,000	7,000	10,000	13,000	16,000	19,000	30,000
100 kilotons	0.3	2.3	3.3	5.6	7.4	10.2	12.5	15.1	24.1
1 megaton	1.0	1.5	2.3	3.7	5.5	7.2	10.0	12.0	22.5
5 megatons	2.3	0.9	1.4	2.3	3.8	5.5	7.2	9.1	17.1
10 megatons	3.2	0.9	1.3	2.1	3.0	4.7	6.3	8.2	15.9

Table 5.3.1 A COMPARISON OF THE TIME OF ARRIVAL OF BLAST WAVES WITH TIME OF ARRIVAL OF PEAK THERMAL INTENSITY, AFTER DETONATION OF 100 KILOTON, 1, 5 AND 10 MEGATON WEAPONS AT AN ALTITUDE OF 5,000 FEET .

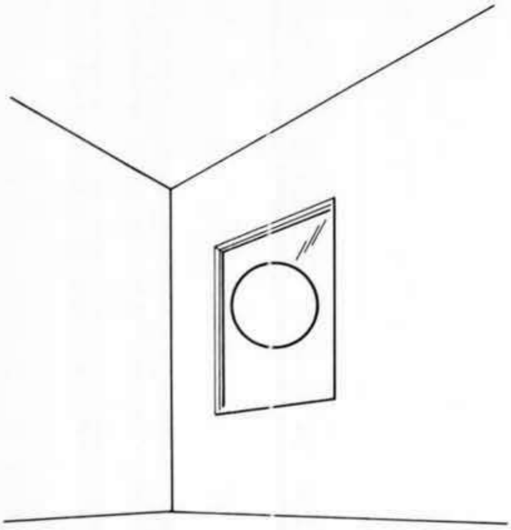


FIG. 5.4.1.a. WHOLE FIREBALL VISIBLE

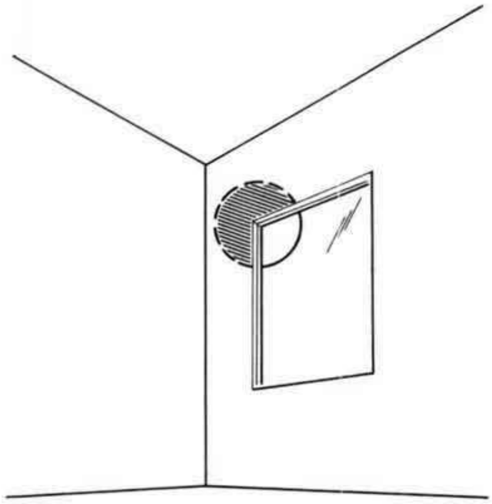


FIG. 5.4.1.b. ONE QUARTER VISIBLE

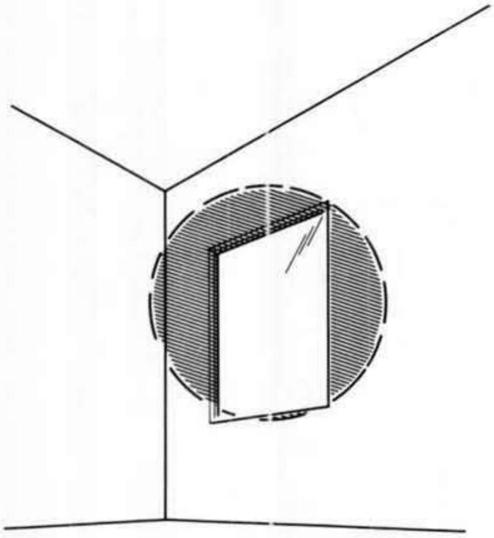


FIG. 5.4.1.c. FIRBALL CLOSER BUT ONE HALF VISIBLE.

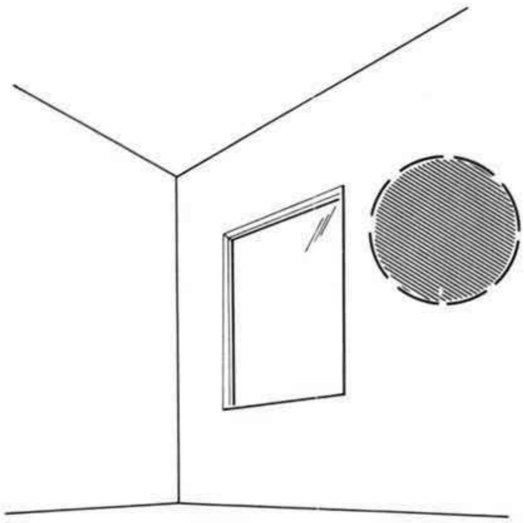


FIG. 5.4.1.d. FIREBALL COMPLETELY OBSCURED BY BARRIER.

FIG. 5.4.1 VISIBLE PORTIONS OF FIREBALL AS SEEN FROM THE POSITION OF A COMBUSTIBLE SITUATED IN A ROOM.

view by the external wall. Thus, no direct heat reaches the target paper. If external shields existed then their effect must be added to those due to the geometry of the room. Unfortunately, although estimating the attenuation of direct rays due to thermal barriers is a fairly simple matter, there is no corresponding method of assessing the shadow effects upon scattered and reflected rays. In most urban areas the number and variety of reflecting surfaces usually prevent any simple estimate of the attenuation of reflected heat being made. However, it is probably reasonable to presume that, due to the presence of exterior and building wall barriers, some diminution of the available reflected and scattered heat takes place. Although it is not necessarily correct, the simplest approach is to assume that the ratio of the total heat actually delivered to a target from direct, scattered and reflected sources, to the total heat from all sources available to the target if no barriers were present, equals the ratio of the apparent surface area of the fireball visible to the target, to the apparent surface area if no barriers were present. This relationship is expressed more concisely in Equation 5.5.1.

$$\frac{Q_{del.}}{Q_{avl.}} = \frac{A_{del.}}{\pi \times \text{Radius}_p^{\,2}} \qquad - 5.5.1$$

where $Q_{del.}$ = amount of heat actually delivered to a target

$Q_{avl.}$ = amount of heat available to a target if no thermal barriers existed

$A_{del.}$ = apparent surface area of fireball visible to the target

Radius_p = radius of the fireball at the instant of maximum thermal intensity (see Equation 3.10.2).

The term "Radius_p" will be made clear in Section 5.7.

5.6 Equation 5.5.1 suggests that if a weapon detonation point is known or assumed, then, by sighting between an ignitable material and the burst, it is possible to determine the extent to which that material will be subjected to the available heat. One of the best techniques of assessing the apparent surface area of a fireball visible to a target was adopted in a survey of ignition points conducted in Boston and Detroit[2]. This was performed by taking a photograph from an ignition point, usually, but not necessarily, located indoors, in the direction

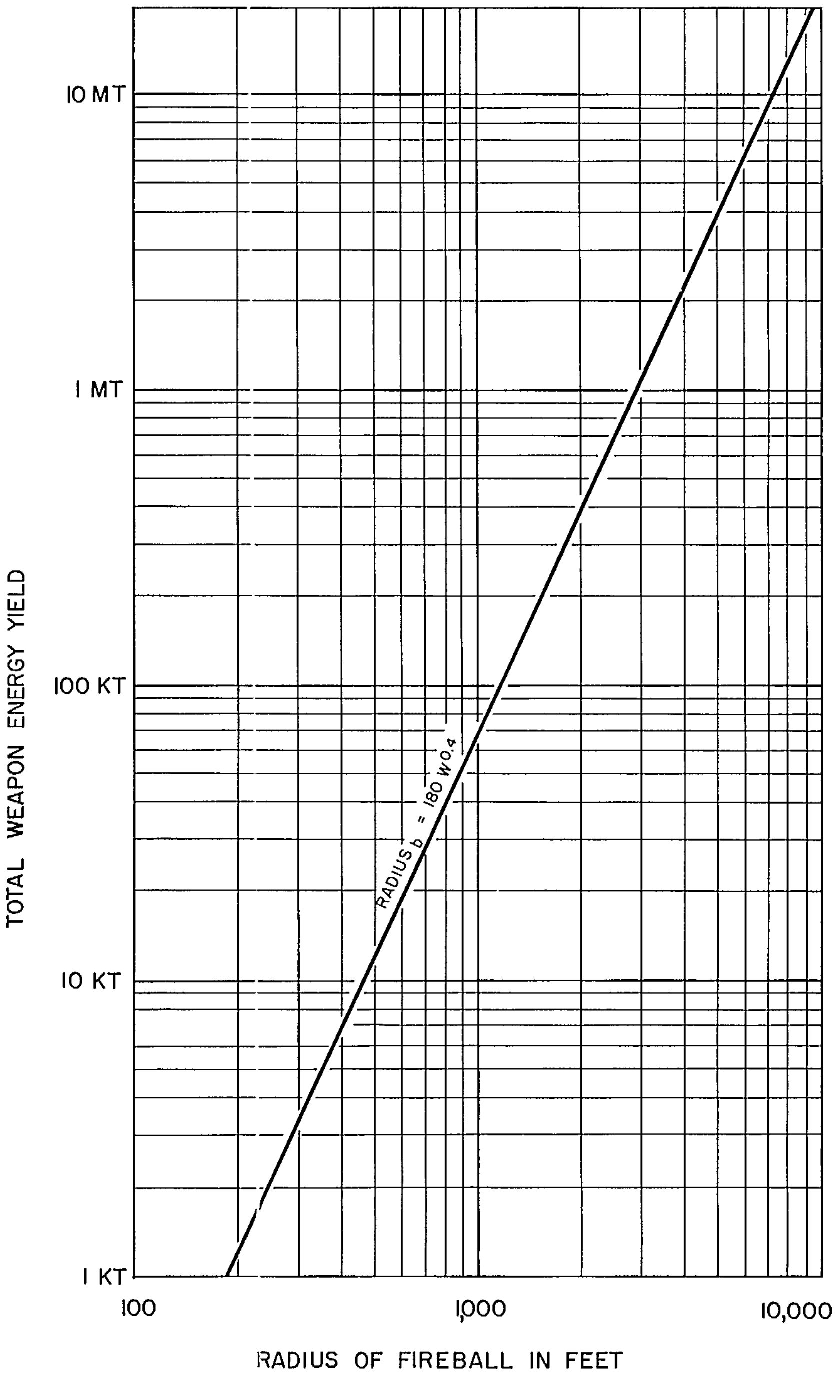


FIG. 5.7.1. RADIUS OF FIREBALL IN FEET WHEN THERMAL INTENSITY ATTAINS MAXIMUM VALUE.

of the centre of an assumed fireball. The picture, of course, recorded the intermediate thermal barriers lying in the path of the direct rays. With due regard to scale, the apparent size of the fireball may be superimposed upon a photographic print and the ratio of the unobscured to the total fireball area may be derived by measurement.

5.7 It is usually sufficiently accurate to consider only the condition when the fireball is emitting maximum thermal power, that is, from Equation 3.10.1, when the time after detonation is 0.032 $\sqrt{W}$ seconds. The radius of the fireball corresponding to this time is given, approximately, by Equation 5.7.1, and presented graphically in Figure 5.7.1.

$$\text{Radius}_p = 180\ W^{0.4} \qquad - 5.7.1$$

where Radius_p = Radius of fireball at 0.032 $\sqrt{W}$ seconds after detonation

W = Total weapon energy in kilotons

During the lapse of time between detonation and the attainment of maximum power, the fireball ascends at a velocity of approximately 400 feet per second so that its altitude at maximum power is given by Equation 5.7.2. Therefore, it is more accurate to sight the camera in line with the point corresponding to the centre of the risen fireball.

$$\text{Altitude of fireball at maximum thermal power emission} = \text{Altitude of detonation point} + (12.8 \times \sqrt{W})\ \text{feet} \qquad - 5.7.2$$

where W = total weapon energy yield in kilotons

5.8 If greater precision is desired, it is necessary to trace the growth and ascent of the fireball from detonation, when the size is substantially zero, through the instant of maximum power, until the fireball reaches its maximum size when its radius is approximately 12 percent greater than that given in Equation 5.7.1. It is rarely worth the extra work involved in carrying out these steps as the accuracy of the estimated velocity of ascent and the size of the fireball does not warrant precise computations. An example of the simpler method is shown below.

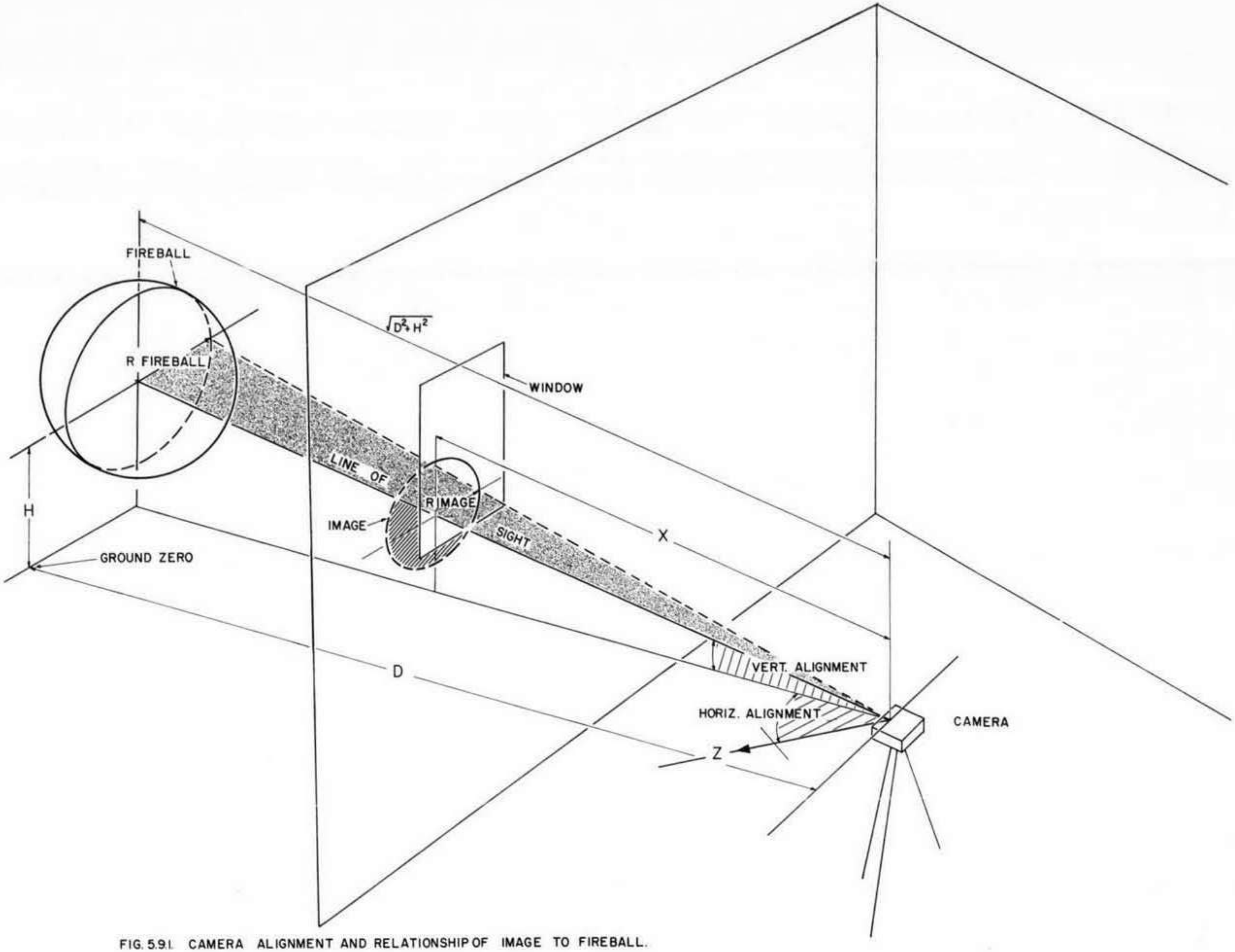


FIG. 5.9.1. CAMERA ALIGNMENT AND RELATIONSHIP OF IMAGE TO FIREBALL.

5.9 Example

A civil defence plan assumes that a 1 megaton weapon may be detonated over a fixed point at an altitude of 5,000 feet and at a distance of 20,000 feet, measured horizontally, from a building in which combustibles are stored. The combustibles are located 12 feet from a wall containing a window that faces towards the detonation point. There are no exterior thermal barriers. It is required to assess the value of the thermal shielding provided by the building wall.

Solution

A camera is located at the combustibles.
With the aid of a compass and a map, the camera is oriented in the horizontal plane so that it is directed towards an imaginary vertical line passing through the assumed detonation point.

From Equation 5.7.2

The altitude of the fireball at maximum thermal emission $= 5{,}000 + (12.8 \times \sqrt{1{,}000})$ feet

$= 5{,}400$ feet

With the aid of a vertical protractor, the camera is tilted through an angle of $\tan^{-1} \dfrac{5{,}400}{20{,}000}$, i.e. 15.1°, in the vertical plane.

A photograph is taken and the centre of a developed print is marked to indicate the centre of the fireball.

From Equation 5.7.1 (or Figure 5.7.1)

Radius of fireball $= 180 \times 1{,}000^{0.4}$ feet
$= 2{,}850$ feet

To find the radius of the fireball image on the window, the simple geometrical relations shown in Figure 5.9.1 may be used.

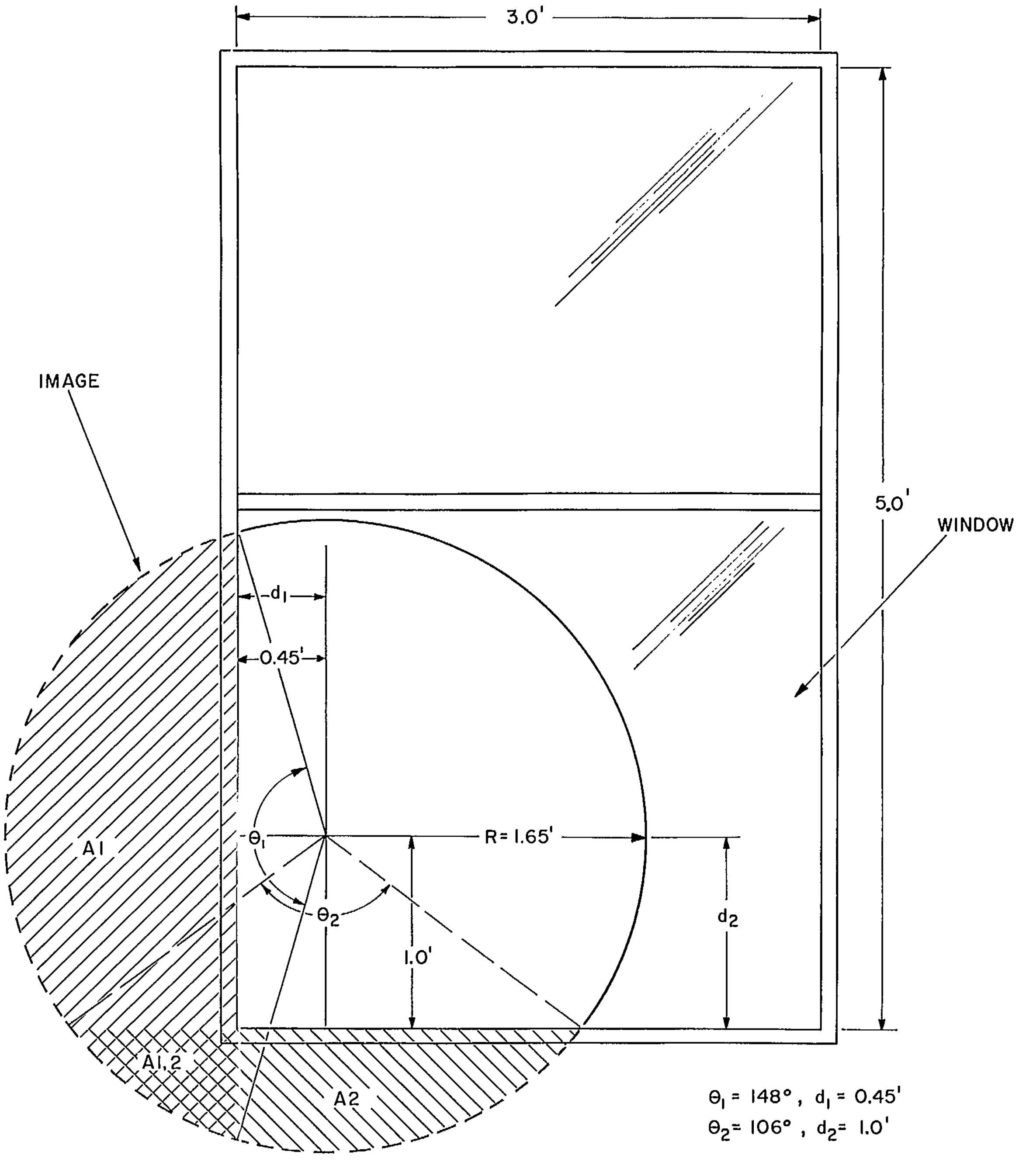


FIG. 5.9.2 IMAGE OF FIREBALL AS SEEN BY CAMERA AT TIME OF MAXIMUM INTENSITY OF RADIATION. SHADED AREAS REPRESENT OBSCURED PORTION OF IMAGE.

Radius of image $= \frac{X \times \text{Radius}_p}{\sqrt{H^2 + D^2}}$

$= \frac{12 \times 2{,}850}{\sqrt{5{,}400^2 + 20{,}000^2}}$

$= 1.65$ feet

The true size of the window is compared to corresponding sizes measured on the photograph to establish the scale.

A circle of scaled radius of 1.65 feet is drawn with centre at the centre of the photograph.

The result is shown diagrammatically in Figure 5.9.2.

Area of fireball image $= \pi \times 1.65^2$ sq. feet

$= 8.6$ sq. feet

The area of the circle "visible" to the camera may be measured by planimeter, by counting squares on the superimposed piece of transparent graph paper or by trigonometical methods.

Applying trigonometrical methods to Figure 5.9.2.

Invisible fraction of image $= \frac{A_1 + A_2 - A_{12}}{8.6}$

where $A_1 = \frac{1}{2} \times \text{Radius}^2 (\theta_1 - \sin \theta_1)$

$= \frac{1}{2} \times 1.65^2 \left(\frac{148 \times \pi}{180} - \sin 148^\circ \right)$

$= 2.8$ sq. feet

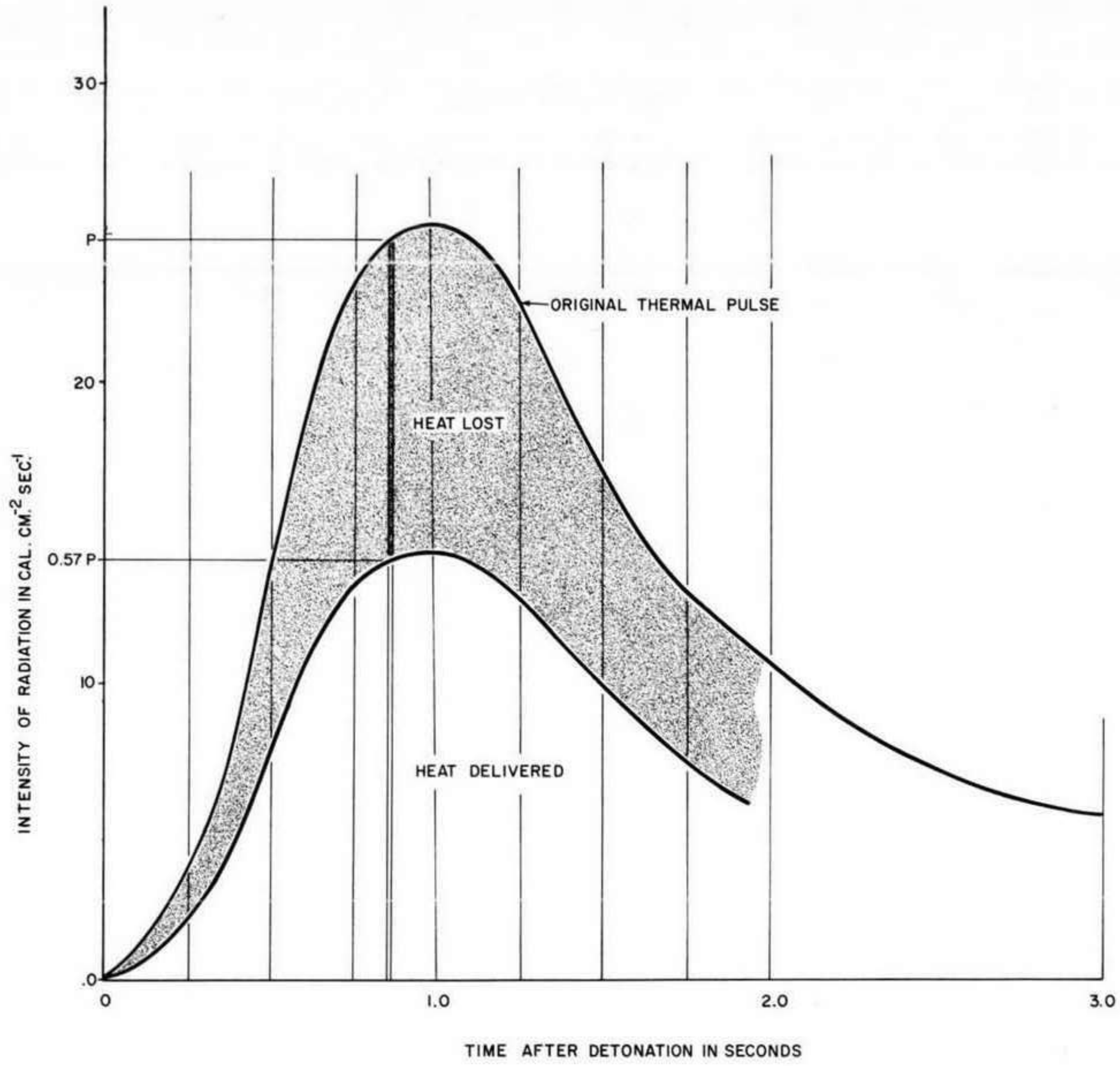


FIG. 5.9.3. ORIGINAL AND DELIVERED PULSE DIAGRAMS FOR A I MEGATON WEAPON, DETONATED AT A DISTANCE OF 20,000 FEET, AT AN ALTITUDE OF 5,000 FEET, 57% UNOBSCURED.

$$\text{Similarly } A_2 = \frac{1}{2} \times 1.65^2 \left(\frac{106 \times \pi}{180} - \sin 106^\circ \right)$$

$$= 1.2 \text{ sq. feet}$$

$$\text{and } A_{12} = \frac{1}{2} \times \text{Radius}^2 \times \left(1 - \cos \frac{\theta_1}{2}\right)\left(1 - \cos \frac{\theta_2}{2}\right)$$

(Assuming A_{12} is nearly a triangle)

$$= 0.3 \text{ sq. feet}$$

$$\text{Invisible fraction of image} = \frac{2.8 + 1.2 - 0.3}{8.6}$$

$$= 0.43 \qquad \therefore \ \underline{\text{Visible fraction} = 0.57}$$

Therefore, only 57% of the available heat is delivered to the combustibles. Plots of the thermal intensity against time may be drawn for the conditions where no thermal barriers are present and where only 57% of the available power impinges on the combustibles.

These have been produced in Figure 5.9.3 by using Equation 4.11.2 and assuming, for simplicity, that $\tau_A = 1$.

Answer

5.10 The foregoing discussion and example show that a further modification should be added to those due to the atmospheric transmission effects discussed in Section 4. In the example it has been demonstrated that, for the particular set of conditions postulated, the intensity, and therefore, the energy delivered to the combustibles was only 57% of that available if no barriers had existed. As a similar procedure may be adopted for any set of conditions, it may be readily appreciated that a coefficient of positive numerical value less than unity may be applied to Equations 4.11.1, 4.11.2 and 4.11.3 to make allowance for shielding effects. Thus, these equations may be rewritten in the forms given in Equations 5.10.1, 5.10.2 and 5.10.3.

$$Q = \tau_A \times \tau_B \times \frac{W \times 10^8}{4.51 R^2} \qquad - 5.10.1$$

$$P = \tau_A \times \tau_B \times \frac{2 \times 10^{14}}{W R^2} \times t^3 \times e^{\frac{-93.75 t}{\sqrt{W}}} \qquad - 5.10.2$$

GLAZING AND WINDOW SCREEN COMBINATIONS	TRANSMISSION COEFFICIENT τ_w
None	1.00
Single Window Screen	0.67
Single Pane Glazing	0.56
Single Pane Glazing, Single Screen	0.37
Double Pane Glazing	0.31
Double Pane Glazing, Single Screen	0.21

Table 5.11.1 TRANSMISSION COEFFICIENT, τ_w, FOR RADIANT HEAT THROUGH WINDOW GLASS AND MESH SCREEN[2]

$$P_p = \tau_A \times \tau_B \times 3.4 \times 10^8 \times \frac{\sqrt{W}}{R^2} \qquad - 5.10.3$$

Where τ_B = coefficient of value $0 < \tau_B < 1$ representing the fraction of the total projected area of fireball visible from a target (see example in Section 5. for method of determination).

and τ_A = Coefficient given in Table 4.10.1

and other symbols are as given in Equations 3.9.1, 3.9.2 and 3.10.2.

5.11 There is a further important effect by which heat entering a building is reduced. This is the loss that occurs at glass and mesh screen in windows or doors. When heat from a nuclear weapon impinges upon a window pane, some is reflected or absorbed while the remainder is transmitted into the building. If the rays are incident normal to the plane of the glass or screen, maximum transmission occurs. As the incident rays become more closely parallel to the glass or screen, the transmission decreases. To a certain extent reflection losses are dependent on the slight surface imperfections that result from the manufacture of glass. That is, there is often a superficial waviness affecting the reflection characteristics. However, heat transmission from nuclear weapons has been studied for normal incidence on single strength window glass, a type commonly used in Canada, in various combinations with screen mesh. The results[2] are reproduced in Table 5.11.1. The values in the table are given as that fraction of the incident heat which is actually delivered through the glass to the interior of the building.

5.12 Therefore, for combustible targets situated within a building it is necessary to apply a further modification to the power and energy delivery equations to make allowance for window losses. However, it should be remembered that these losses occur when a substantial part of the thermal delivery precedes the arrival of a blast front (see Section 5.3). Nevertheless, Equations 5.10.1, 5.10.2 and 5.10.3 should, more properly, be written in the forms given in Equations 5.12.1, 5.12.2, 5.12.3 . For the purpose of this report, these relationships represent

$$Q = \tau_A \times \tau_B \times \tau_W \times \frac{W \times 10^8}{4.51\ R^2} \qquad - 5.12.1$$

$$P = \tau_A \times \tau_B \times \tau_W \times \frac{2 \times 10^{14}}{WR^2} \times t^3 \times e^{\frac{-93.75t}{\sqrt{W}}} \qquad - 5.12.2$$

$$P_p = \tau_A \times \tau_B \times \tau_W \times 3.4 \times 10^8 \times \frac{\sqrt{W}}{R^2} \qquad - 5.12.3$$

where τ_A = coefficient given in Table 4.10.1.

τ_B = coefficient of value $0 < \tau_B < 1$, representing one fraction of total projected area of fireball visible from the target material (see example in Section 5.9 for method of determination).

τ_W = coefficient given in Table 5.11.1.

the final form of the power and energy equations applicable to weapons detonated at altitudes of less than 100,000 feet. It must be borne firmly in mind that they are no better than fair approximations and that their use should be governed accordingly.

SECTION 6

COMBUSTIBLES AND COMBUSTIBILITY

6.1 Having discussed the delivery of heat from a nuclear weapon in the preceding sections, it is now necessary to attempt to relate the findings to the creation of fires and, thereby, to establish the limits of distance from ground zero within which substantial fire damage may result. As a preliminary measure, it appears logical to determine the combustibles that are likely to govern the extent of the zone within which primary ignitions (i.e. ignitions resulting directly from a weapon's thermal radiation) may occur.

6.2 It is well known that combustibles may be gaseous (e.g. methane), liquid (e.g. gasoline) or solid (e.g. wood), and that some are more readily ignitable than others. Most of the fuels that ignite violently are usually well protected from chance sources of heat or open flame. For example, gasoline is usually stored in buried tanks at automobile stations and natural gas is conducted through pipes with a substantial cover of soil. Thus, when it is borne in mind that heat from a nuclear weapon is quickly attenuated by an opaque material, it may be concluded that the most highly combustible fuels do not necessarily provide a high degree of hazard. Furthermore, in the case of liquids, the heat impinging on one surface is "diluted" through the whole volume, and, if that volume is substantial, the resulting rise in temperature may be quite insignificant. Generally speaking, as distance from the detonation point increases, the likelihood of commonly occurring liquid and gaseous fuels making a significant contribution to the number of primary ignitions diminishes very quickly.

6.3 Often, a greater risk of ignition occurs when solid fuels are exposed to radiant heat. By far the largest and most important group of combustible solids consists of cellulosic materials, of which some of the better known examples are wood, paper, leaves, grass, cotton, linen, rayon and many plastics. This group comprises such a large variety of possible forms and characteristics that it may be guessed that not all exhibit an equal readiness to ignite or to sustain combustion. Reasonably, the only fuels of interest are those of common and profuse occurrence that ignite easily and sustain ignition. The selection is aided by simple rules proposed by Professor G.I. Finch. These segregate solid fuels into three categories that relate the shape of the fuel to its proneness to ignite.

6.4 If the term specific surface is defined to mean the total surface area, in square centimeters, per gram of weight of a solid, then Finch's rules may be stated in the following manner.

Tinder: A solid fuel, of specific surface exceeding 20 square centimeters per gram, that may be ignited with a domestic match and which will continue to burn after the match is withdrawn. Examples of tinder are paper, cardboard and cellulosic textiles.

Kindling: A solid fuel of specific surface in the range of 2 square centimeters per gram and 20 square centimeters per gram. Kindling ignites and burns only when it is associated with sufficient tinder to sustain a fire. An example of kindling is 1/2 inch thick plywood.

Bulk Fuel: A solid fuel of specific surface less than 2 square centimeters per gram and having a minimum thickness of 1/2 inch. Bulk fuel requires the presence of burning kindling to initiate ignition and sustain combustion.

6.5 Although the foregoing rules were primarily intended for use in normal building fires, they may be applied to conditions near the boundary of the primary ignition zone. (Nearer ground zero the radiant heat may be sufficiently intense to eliminate the need for the presence of tinder and possibly even kindling to ignite bulk fuel). From them, it may be seen that the materials most likely to ignite are tinders. While tinders comprise a vast variety of materials, it is really only necessary to select those that are common to and plentiful in most areas. There is little virtue in selecting, say, celluloid, for, although it ignites very readily it is not likely that many buildings will have a supply in locations exposed to a weapon's thermal effects. Therefore, intuition indicates that probably the most common tinder fuels are tree foliage, paper and textiles.

6.6 The burning of tinder is usually of little interest unless it is situated where it may ignite kindling which, in turn, may initiate a fire in bulk fuel. While it cannot be suggested that every ignition of tinder results in substantial property loss, nevertheless, due to their environments, some tinders are more likely to cause major fires than others. Thus, despite their wide occurrence, leaves tend to be rather poor tinder except when they are dry or dead. In most seasons of the year, they burn poorly and do not sustain combustion very well. Furthermore, their proximity to valuable kindling and bulk fuels in urban areas is not always sufficiently close to incur a high measure of hazard. On the other hand, paper and textiles are usually associated with the interior of buildings. When indoors, they are not only in much closer proximity to valuable property than leaves, but also, they are not greatly affected by seasonal changes nor are they subject to wide variations in moisture content. Therefore, although they may not receive as much heat as leaves, due to attenuation in window glass and screen and a building's

own shielding effects (see Section 5), on the whole, they appear to present a greater fire hazard than leaves.

6.7 When considering textile tinders, it is natural to think of window drapes where a building's self-shielding is likely to be least effective. These appear to present a higher hazard than paper, especially in the event of a night attack when drapes are closed. Under this condition, they may effectively shield other tinder in a building while they absorb a substantial part of the delivered heat. However, some commercial and industrial buildings are not equipped with drapes; many buildings have drapes woven of incombustible glass fibres or textiles treated with fire retardants; others are equipped with incombustible metal venetian blinds. Furthermore, many modern fabrics are light coloured and have a surface sheen that tends to reflect heat and to diminish thermal absorption.

6.8 On the other hand, paper appears to occur more or less profusely and in a random fashion in all types of buildings. Much of it contains dark printing dyes that may be expected to act as a good heat absorber, and a great deal of it has a matt finish of a low reflecting quality. Weighing the respective merits of textiles and paper, it seems likely that the latter is probably a rather better choice of tinder than the former.

6.9 If it is accepted that matt, dark-dyed paper, such as newspaper, is the most commonly available tinder, the discussion may proceed on the basis, that, near ground zero, thermal damage is assumed to be high. It seems reasonable to suppose that, as distance from ground zero increases, the risk of primary ignition diminishes until at some limiting distance, ignition is confined to paper. Beyond this limit, primary ignitions are likely to be sporadic and the ability to control an outbreak of fire is probably greatly enhanced. Thus, the limiting distance defines the boundary of a zone in which primary ignitions are likely to occur and in which severe damage may be anticipated due to fire spread.

SECTION 7

IGNITION OF CELLULOSIC SOLID MATERIALS

7.1 When a cellulosic solid fuel is subjected to thermal irradiation, hot volatiles are evolved from the heated surface. If these gases are emitted with sufficient chemical and physical energy, and if there is sufficient atmospheric oxygen available to provide a properly proportioned mixture of fuel and air, it is likely that flaming ignition may result. If this occurs, flame may flash back along the volatile jets towards the parent solid and inflict damage or destruction upon it. This process, termed flaming ignition, is probably the most familiar form of burning. However, if ignition may be described by its effect upon the parent material, then it may occur in three distinctly different forms.

7.2 The first involves a spontaneous sustained flaming of the volatiles that produces a profound alteration in the chemical and physical properties of the parent. It usually occurs when a high intensity of irradiation is maintained for a sufficiently long period to involve the solid deeply, so that, even when the source of heat is removed, the combustion process continues. This form of ignition is associated with high surface temperatures, and, in some complex manner, with the thickness of the material.

7.3 The second form is often referred to as transient flaming ignition. Although it has many of the characteristics of spontaneous sustained flaming ignition, it is considerably less violent and, usually, the flaming ceases when the source of heat is removed. There may be several reasons for this. One is that the high intensity irradiation has not been maintained long enough for sustained ignition to become established. Or, it may be due to an insufficient supply of voltatiles or air to produce a combustible mixture. It may also be due to the proper mixture occurring too far from the parent body to affect it in any marked degree. A further possible explanation will be discussed later in Section 7.14. Regardless of the reason, this type of ignition usually fails to involve the solid matter to any great depth, but, rather, the damage inflicted is substantially confined to the surface.

7.4 The third type of ignition produces a hot, glowing destruction or charring of the parent material. This type of damage is usually associated with relatively low intensities of radiation that are maintained for prolonged periods. The gases are emitted too slowly or with too little energy to flame in the presence of atmospheric oxygen. A similar effect may be produced by limiting the available oxygen rather than the supply of volatiles. This latter process is the basis of charcoal production.

7.5 The foregoing three types of ignition effects are valid when only radiant heat is applied. The situation changes somewhat when a pilot flame or spark is introduced into the volatile stream. However, if it is assumed that, near the boundary of the primary ignition zone, the blast front lags substantially behind peak thermal intensity, then it is probably reasonable to conclude that combustion occurs without pilot ignition. From a qualitative appraisal of the three available mechanisms, it seems obvious that the greatest hazard of fire-spread exists in the case of spontaneous sustained flaming ignition. Thus, it is important to be able to predict the type of ignition that may result from the thermal delivery of a nuclear weapon of a known total energy yield. For example, in Figure 3.9.1, the thermal pulses of two weapons, one of 100 kilotons total energy yield, the other of 10 megaton total energy yield, each delivering 30 calories per square centimetre, are presented. An inspection of the curves shows that the peak intensity of the latter is much less than that of the former. As all three types of ignition depend on intensity and on time, it is possible that one pulse may cause sustained flaming ignition of paper while the other may cause only transient flaming, or both may cause sustained flaming. Unfortunately, there is no simple mathematical method available by which the type of ignition may be predicted.

7.6 The difficulties stem from the complexities of the chemical and physical changes that occur during heating. While a general mathematical expression may be formulated [3] to relate all of the basic mechanisms leading to ignition, it is not possible to solve it without making assumptions of a quality that tend to make a solution suspect. This has led to many attempts to discover a simpler mathematical model to explain the ignition process. So far, none has received universal acceptance. In the main, these models may be separated into two groups. One tends to emphasize an approach by way of the energy of the volatile flow; the other relies upon concepts of heat transfer. Despite the convenience of accepting one or other of these models, most research workers concede that, in practice, the energy of the volatiles and heat transfer processes are necessarily complementary to each other.

7.7 Those hypotheses that propose correlating volatile emission with ignition are usually based on Arrhenius' equation. This relation is expressed in a shortened form in Equation 7.7.1. Usually the value of E in this equation is assumed to be constant, although there is reason to believe that it may, in fact, vary to correspond with a number of complex chemical reactions that take place during irradiation.

$$\frac{\partial \omega}{\partial t} \propto e^{\frac{-E}{RT}} \qquad - 7.7.1$$

where ω = the concentration of reactant volatiles, in gm. cm^{-3}

t = time, in seconds

E = effective energy required to activate 1 mol. of reactant to a state where reaction may occur, in calories. mol^{-1}

R = universal gas constant

T = absolute temperature, in ^oK

Nevertheless, there have been a number of successful attempts to explain some ignitions produced in experimental work by means of the basically simple Arrhenius equation, despite the possibly erroneous assumption that E is constant for a given combustible cellulosic material. Bamford, Crank and Malan[4] used a criterion shown in Equation 7.7.2 which implies that at some critical rate of voltatile emission, sustained burning is likely to occur. From experiment, they suggest that this rate is 2.5 x 10^{-4} grams per square centimetre per second. On the other hand Lawrence[5] found that, at ignition, the rate of evolution was consistently greater than that proposed by Bamford, Crank and Malan. Sauer and Williams[6] have applied a slightly different approach in which they attempt to correlate thermal damage with a critical volatile content remaining in the parent body. However, this method has been criticized

$$\int_0^{\ell} \frac{\partial \omega}{\partial t} \, dx \geqslant N \qquad - 7.7.2$$

where N = critical flow rate of volatiles in $gm.cm^{-2}.sec^{-1}$

ℓ = thickness of solid body

and x = depth from surface of solid body

and, other symbols are as defined in Equation 7.7.1

on the basis that the value of E for a given material is not sufficiently accurately known.

7.8 Those who propose the use of heat transfer methods to provide a mathematical model, point out that in Arrhenius' equation (see

Equation 7.7.1) the rate of evolution of volatiles depends on temperature, T. Therefore, with some justification, they suggest that, as heat transfer methods provide a solution in terms of temperature, they are, in effect, including evolution rate within their model. For convenience, they use the temperature of the parent material rather than that of the volatiles. As the two are related, this step does not appear to be unreasonable. However, there seems to be a considerable divergence of opinion on values of temperature that correspond with each type of ignition. In fact, it does not appear that this approach can clearly distinguish between the three basic forms of ignition.

7.9 There are also a number of difficulties that arise to introduce inaccuracies in mathematical solutions to heat transfer problems. Most of these are concerned with heat losses. Fortunately, they are of a character that does not always lead to serious errors. However, it is better that they be discussed, at least in a qualitative manner, so that some appreciation of the difficulties confronting the mathematician may be made evident.

7.10 When heat impinges on a solid, some is lost due to reflection. However, the rate of loss changes as the surface colours change under irradiation. In the case of matt-surfaced paper containing dark-coloured dyes this is not likely to be important. The heat that is accepted by the material serves to increase its temperature. One result of this is that the body itself becomes a radiator capable of emitting or re-radiating heat. Furthermore, the natural convective flow of air tends to cool the body. This effect is rather difficult to predict with any accuracy due to its variability with a number of associated phenomena, and to the fact that it takes some time to become established as a significant mechanism of cooling. Therefore, it is not usually important in very short term irradiation such as may be expected from weapons of small energy yield. However, as convective and re-radiative losses are of the same order of magnitude in an established heat system[7] and, as the criterion for primary ignitions has been assumed to be matt-surfaced papers containing dark dyes (see Section 6) so that reflection losses are usually small, it is often possible to neglect heat losses completely. Although this may be seen to introduce some error into a solution, it greatly simplifies the mathematical treatment.

7.11 The heat that is not lost is conducted into the solid where it increases the temperature of the material with which it is brought in contact. The mechanism by which this occurs may be expressed in the form of Equation 7.11.1. In this relationship K, ρ and c are assumed

$$\frac{\delta T}{\delta t} = \frac{K}{\rho c} \times \frac{\delta^2 T}{\delta X^2} \qquad - 7.11.1$$

where T = absolute temperature, in ^{o}K

t = time of irradiation, in seconds

x = depth behind heated surface, in cm.

K = thermal conductivity of material, in cals. cm. cm^{-2}. sec^{-1}. $^{o}K^{-1}$.

ρ = material density, in gm. cm^{-3}

c = specific heat capacity, in cals. gm^{-1}. $^{o}K^{-1}$

to remain substantially constant throughout irradiation. Although this assumption is not necessarily true, it does not appear to lead to serious error. Furthermore, this expression is valid only where heat is applied in a uniform manner and normal to one face of a solid body and where lateral thermal diffusion is negligible.

7.12 For a solid of finite thickness it is necessary to prescribe initial conditions at the start of irradiation and boundary conditions existing during irradiation, both at the receiving face and at the opposite, cool, face. The initial conditions applicable to this discussion are given in Equation 7.12.1. The boundary condition at the heated faces is expressed in Equation 7.12.2.

$$\text{For } t = 0 \text{ and } 0 < x < \ell \text{ then } T = T_o \qquad - 7.12.1$$

and for $t > 0$ and $x = 0$ then

$$-K \frac{\delta T}{\delta x} = \tau_A \times \tau_B \times \tau_W \times \frac{2 \times 10^{14}}{WR^2} \times t^3 \times e^{\frac{-93.75 t}{\sqrt{W}}} \qquad - 7.12.2$$

also, for $t > 0$ and $x = \ell$ then $\frac{\delta T}{\delta x} = 0$ - 7.12.3

where T_o = ambient temperature at start of irradiation, in ^oK

ℓ = thickness of solid, in cm.

and other terms are as defined in the foregoing text.

which postulates that the power input is equal to that delivered by a nuclear weapon (see Equation 5.12.2). Equation 7.12.3 sets the boundary condition for the back, cool, surface of the irradiated solid. While it is not possible to know exactly what condition will exist at this boundary, the writers suggest that a condition of no heat flow is probably reasonable.

7.13 By solving Equation 7.11.1 with the above initial and boundary conditions, it is possible to predict temperatures at any depth in the solid at any time. If temperatures corresponding to the three types of ignition are known, then it would seem that the problem of predicting ignition is solved. Unfortunately, this is not the case as there appears to be disagreement among the authorities concerning the value of these temperatures and the depth at which they should be taken. Experimental data obtained in some ranges of thermal power delivery, favour accepting a temperature at the heated surface, while other data show that the temperature of the opposite, cool, face may be a good criterion.

7.14 The adoption of any temperature criterion is strongly influenced by an effect noted by Simms[8] during experimental work on the irradiation of cellulosic solids. He found that flaming ignition occurred where the flow of volatiles mixed turbulently with air, and that, if turbulence did not occur within a short distance of the heated surface, ignition often failed to result. This was demonstrated by comparing the effects of two dissimilar sources of radiant heat upon a cellulosic target. One was a gas-fired panel; the other was a tungsten filament lamp whose rays were reflected from an ellipsoidal mirror to focus upon the specimens. The former was found to cause substantial air draughts of velocities in the neighbourhood of 50 feet per second. These tended to change the volatile flow from a laminar to a turbulent condition closer to the targets than did the tungsten filament source that produced no draughts. Except where turbulence occurred naturally, for the latter source flaming ignition sometimes failed to result. This was found to be true even when the surface and volatile temperatures substantially exceeded those resulting from flaming ignition caused by the gas-fired panel.

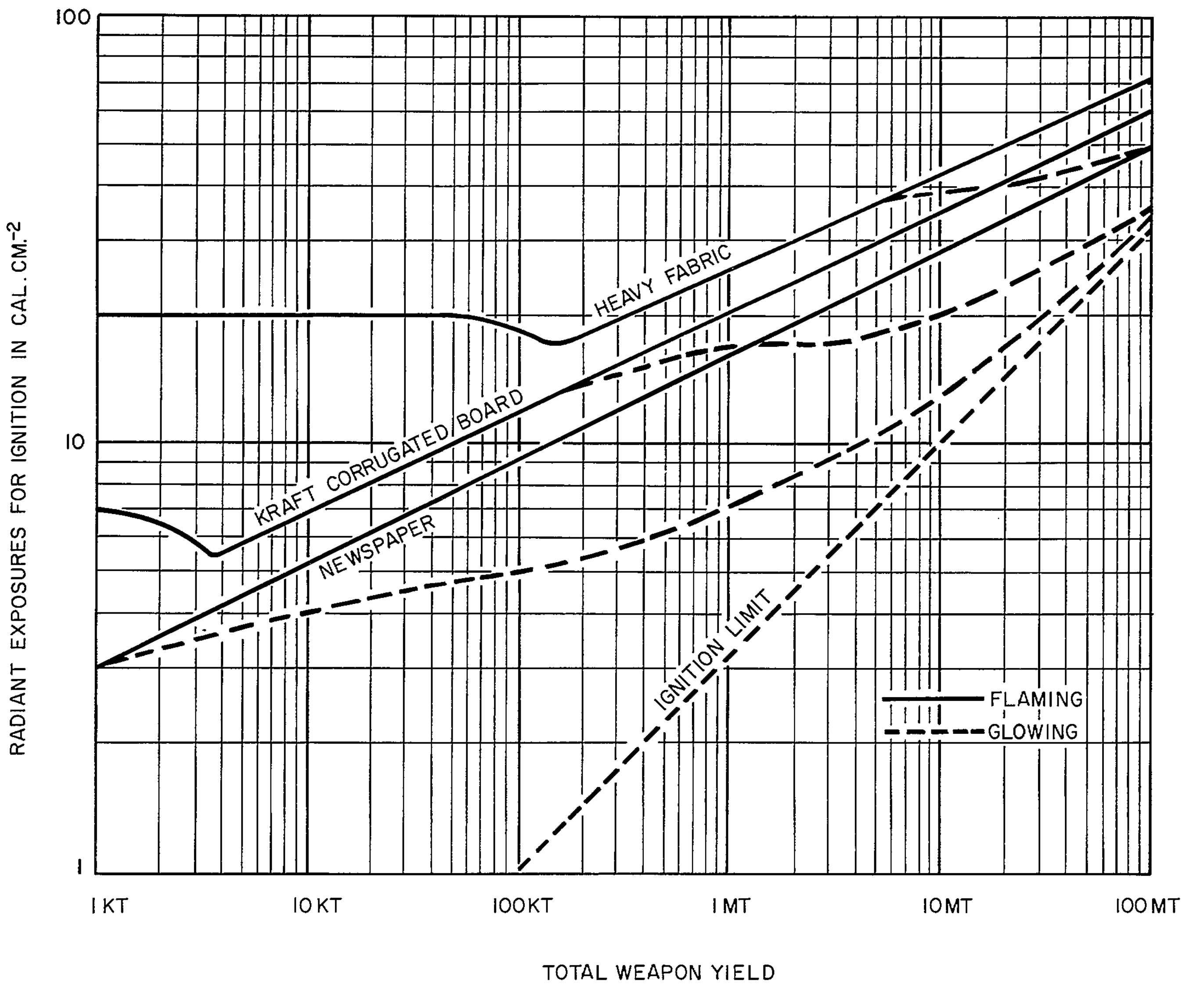


FIG. 7.16.1 RADIANT EXPOSURES TO IGNITE MATERIALS (40 TO 50% RELATIVE HUMIDITY) AS A FUNCTION OF TOTAL WEAPON YIELD, TAKEN FROM "THERMAL RADIATION AND FIRE EFFECTS OF NUCLEAR DETONATIONS" BY S. MARTIN AND A. BROIDO.(9)

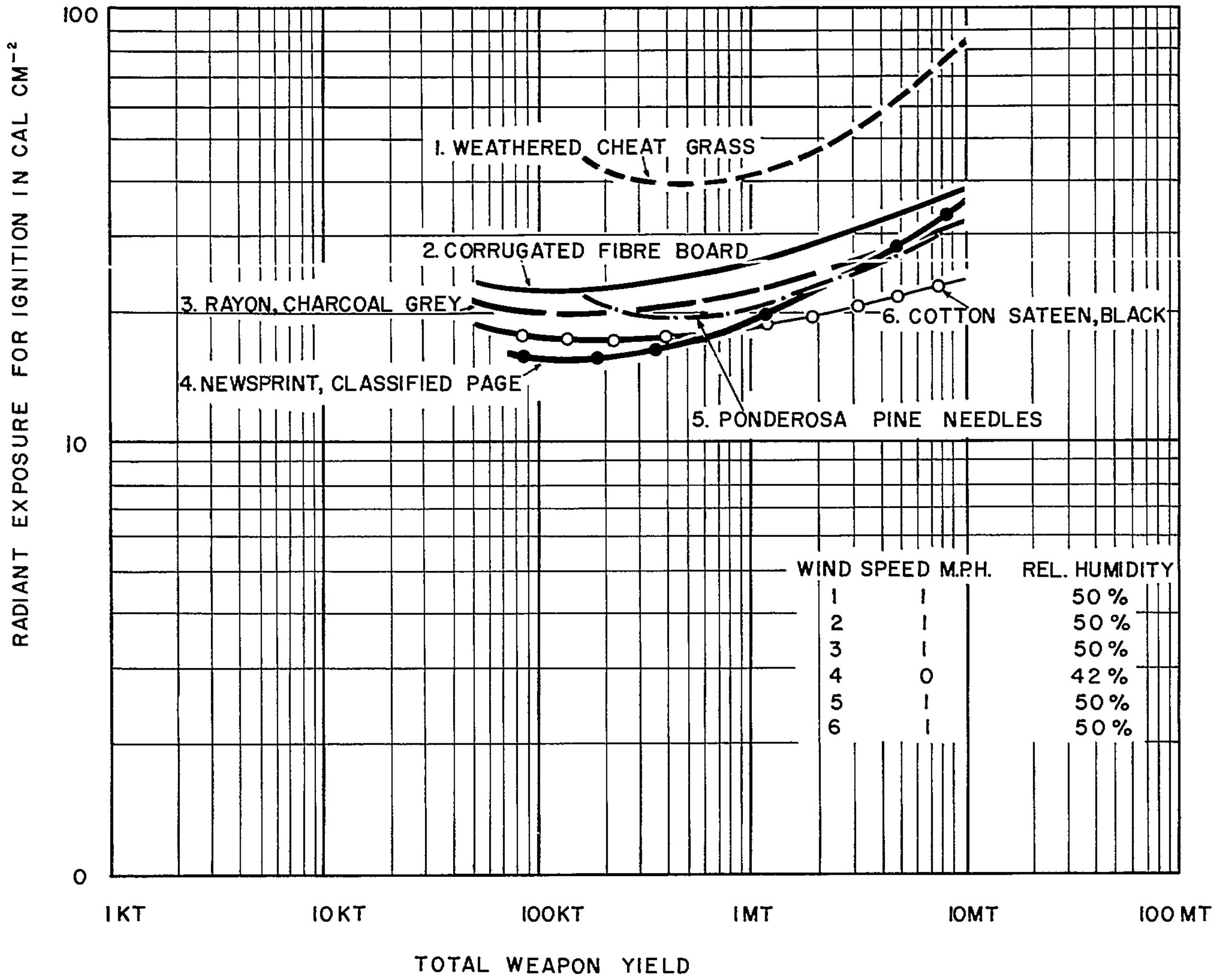


FIG. 7.16.2 RADIANT EXPOSURES TO IGNITE VARIOUS MATERIALS AS A FUNCTION OF TOTAL WEAPON YIELD, TAKEN FROM "TECHNICAL OBJECTIVE AW-7" by J. BRACCIAVENTI & F. DEBOLD, JULY 1960.

7.15 From Simm's work it is reasonable to conclude that attempts to correlate temperature with ignition may be of limited scope. It also infers that experimental work on the thermal emission from nuclear weapons must be conducted with equipment that will reasonably closely simulate the environment in which ignitions may occur. For example, in most buildings one is not likely to encounter air velocities of 50 feet per second except possibly near fans, air-duct grilles and registers or open windows. Therefore, prior to the arrival of blast, it would appear that sources akin to Simms' reflected heat equipment will produce a closer approximation to conditions prevailing immediately following detonation than draught-producing apparatus.

7.16 From the foregoing discussion it is probably obvious that mathematical methods of predicting ignitions are fraught with difficulties. Hence, it is necessary to rely heavily on purely experimental data. Fortunately, a considerable amount of work has been carried out within recent years, principally by the United States Naval Radiological Defense Laboratories. By using radiant heat sources comparable to Simms' mirror technique, and, by mechanical means, simulating the shape of the thermal pulse delivered by a nuclear weapon, ignition data have been compiled. From these, sets of curves have been prepared to correlate sustained flaming ignition with weapon energies. Two such sets have been reproduced in Figures 7.16.1 and 7.16.2. The former is taken from a report published by Martin and Broido[9]; the latter is due to Braccia-venti and DeBold[10]. Both give values of the thermal energy required to produce sustained flaming in selected tinders plotted against total weapon energy. If the curves for newspaper or corrugated fibre-board are carefully compared in these figures, it may be seen that they do not entirely agree. The discrepancy should not be considered to be too serious when it is remembered that thermal energy and power delivery depend on the square of the slant range from the detonation point to the combustible. For, this infers that fairly minor changes in slant range result in marked changes in thermal delivery.

7.17 It is interesting to compare these curves with the corresponding experimental findings of Martin and Lai[11]. The results of their observations are presented in Figure 7.17.1. While the data in this figure are not quite as simple to use as those of Figure 7.16.1 and 7.16.2, they indicate, in a very striking manner, the relationship of peak power (P_p) and delivered thermal energy (Q) with types of ignition. It may be seen that sustained glowing occurs at fairly low powers and high energies, while transient flaming ignition occurs at high powers and low energies. It will be shown later that this latter condition has a marked effect on the performance of tinders subjected to the radiant emission of high-altitude weapons (see Appendix A). A quantitative comparison of ignition predictions made by Martin and Lai with those suggested by Figure 7.16.1 and 7.16.2 will not be made here. However,

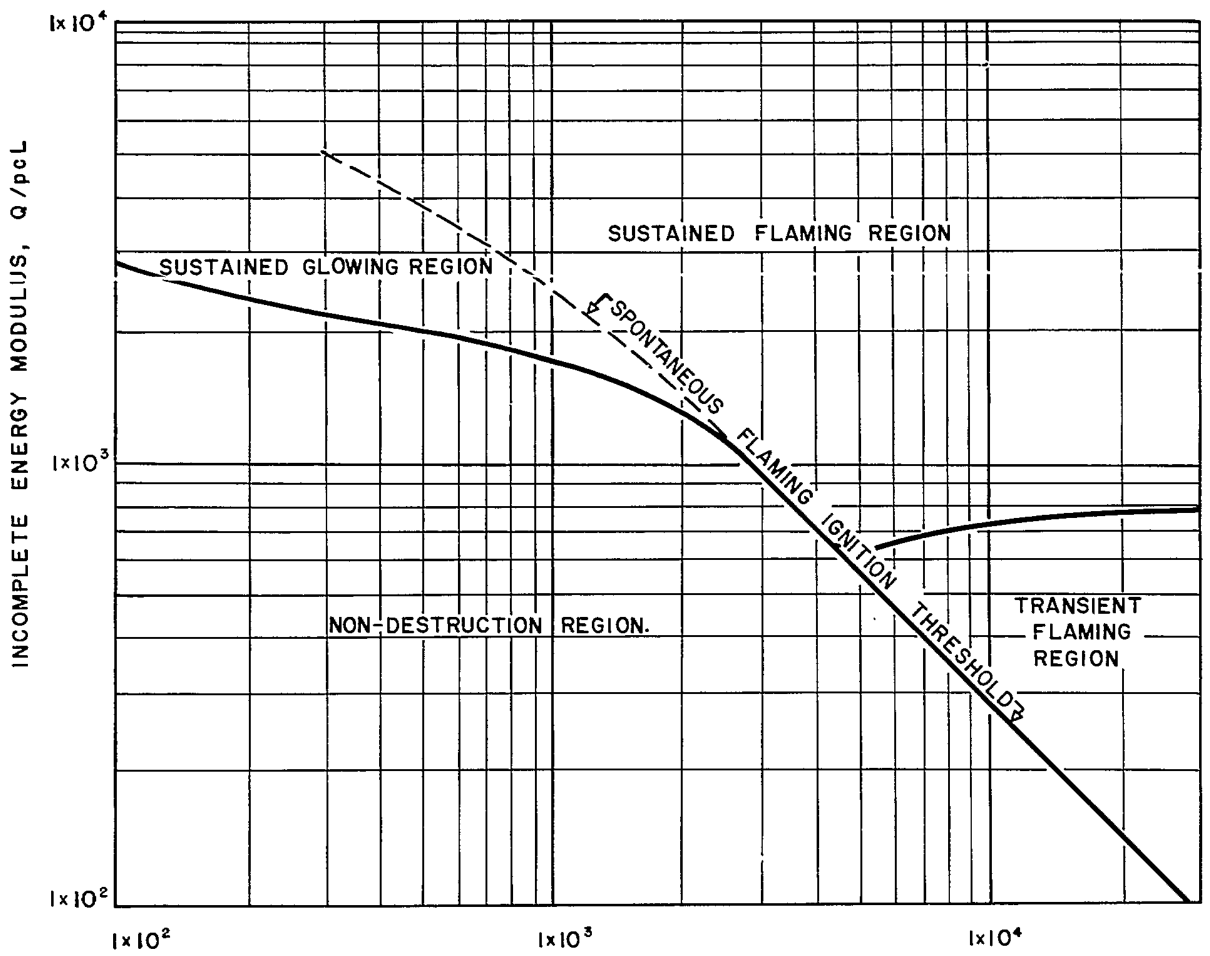


FIG.7.17I:IGNITION BEHAVIOUR PATTERN ILLUSTRATING THE VARIOUS EFFECT-REGIONS AND THE THRESHOLD OF SPONTANEOUS FLAMING, FROM "THERMAL RADIATION DAMAGE TO CELLULOSIC MATERIALS, PART III - IGNITION OF ALPHA CELLULOSE BY PULSES SIMULATING NUCLEAR WEAPON AIR BURSTS." by S.B. MARTIN & W. LAI.

attention is drawn to the values in the abscissae of the three sets of data. Figure 7.17.1 shows terms including peak thermal power; the others show only weapon energy. At first glance there appears to be no immediate relationship, but, Equation 5.12.3. indicates that peak power is defined only by weapon energy, numerical coefficients and a geometrical term. Thus, in a sense, all three figures relate ignition both to thermal energy and to power. This is a point of great importance for it shows that ignition not only depends upon the amount of heat delivered but also upon the rate at which delivery is made.

7.18 The question of which set of data to use now arises. As there is no obvious reason to doubt the validity of any of the results, it is probably easiest to choose the values that give the most conservative answers with the least amount of work. For this reason, the data given in Figure 7.16.1 will be adopted. Having made the choice, it is now possible to achieve the important objective of assessing the maximum distance from ground zero at which selected tinders may ignite and start major fires in buildings.

7.19 It will be recalled from the discussion in Section 6 that matt-surfaced papers containg dark dyes were probably the most likely tinders to cause fires. Newspaper, which occurs abundantly, may be assumed to be representative of this group. Figure 7.16.1 shows two sets of ignition values for newspaper, one for sustained flaming (given as a continuous line), the other for glowing ignition (given as a dotted line). A third line gives values of the lowest limit of thermal energy for a prescribed total weapon energy yield at which ignition may occur. It seems reasonable to assume that where sustained flaming occurs the risk of a major fire resulting is high; on the other hand, at the lower limit of ignition the risk may be assumed to be very low. For example let it be assumed that a 10 megaton total energy yield weapon is detonated. From Figure 7.16.1 it may be seen that sustained flaming ignition of newspaper may occur where the delivered energy is approximately 28 calories per square centimetre. If it is possible to determine at what distance from ground zero energy of this value may be received, then it is reasonable to conclude that major fires will almost certainly occur between that limiting distance and ground zero. Likewise, the ignition limit for a weapon of 10 megaton total energy yield occurs where the delivered energy is approximately 10 calories per square centimetre. Using this value it may be possible to find a second limiting distance from ground zero beyond which ignitions are not likely to occur. Between these two limits, extending outwards from ground zero, the risk of major fires being caused directly by primary ignition diminishes rapidly. This implies that fire fighting at an early stage tends to become progressively more fruitful as the ignitions become more sporadic and less frequent.

7.20 The method of determining these limits is quite simple but rather time consuming. It requires the use of Figure 7.16.1, Equation 5.12.1, Table 4.10.1, Table 5.11.1 and values of τ_B (see Section 5). If the results of a photographic survey are not available τ_B may be assumed to equal unity. The procedure may best be illustrated by the following example.

Example For planning purposes it has been assumed that a 5 megaton total energy yield weapon may be detonated at an altitude of 5,000 feet on a day when the ground is bare of snow and the visibility is 10 miles. It is required to find the distance at which newspaper tinder, located indoors in houses with double pane glazing and no screens, may be ignited to sustained flaming ignition. No photographic survey of the city buildings has been made.

Solution

$$Q = \tau_A \times \tau_B \times \tau_W \times \frac{W \times 10^8}{4.51\ R^2} \qquad - 5.12.1$$

Enter Figure 7.16.1 at 5 megatons

Sustained flaming occurs when Q = 23 calories. cm^{-2}

$\therefore$ Left hand side of Equation 5.12.1 = 23 calories. cm^{-2}

Right hand side of Equation 5.12.1 = $\tau_A \times 1 \times \tau_W \times \frac{5{,}000 \times 10^8}{4.51\ R^2}$

and $R^2 = 5{,}000^2$ + (distance from ground zero to tinder)^2 in feet

Try a distance from ground zero to tinder = 20,000 feet

From Table 4.10.1 τ_A = 0.50

and $R^2 = (5{,}000^2 + 20{,}000^2)\ ft^2$

$= 425 \times 10^6\ ft^2$

From Table 5.11.1 $\tau_W = 0.31$

Right hand side of Equation 5.21.1 $= 0.50 \times 1.0 \times 0.31 \times \frac{5,000 \times 10^8}{4.51 \times 425 \times 10^6}$

$= 40$ calories. cm^{-2}

Therefore the guess of 20,000 feet from ground zero to tinder was an underestimate.

Try a distance from ground zero to tinder $= 25,000$ feet

From Table 4.10.1 $\tau_A = 0.41$ approx.

$\tau_B = 1.0$

$\tau_W = 0.31$

$R^2 = (5,000^2 + 25,000^2)$

$= 650 \times 10^6$ ft.^{2}

Right hand side of Equation 5.12.1 $= 0.41 \times 1.0 \times 0.31 \times \frac{5,000 \times 10^8}{4.51 \times 650 \times 10^6}$

$= 21.6$ calories. cm^{-2}.

Thus, in this case, the trial value of 25,000 feet was over-estimated but obviously not grossly in error from a distance that would result in the required total energy of 23 calories . cm^{-2}. Greater assuracy may be obtained by continuing the trial-and-error process shown above. Alternatively, an estimate may be obtained by linear interpolation between two reasonably close trials. Regardless of the method employed, the assumptions made in selecting a weapon energy, detonation height and meteorological conditions do not warrant an accuracy greater than, say 500 feet. In this example the authors would accept an estimate of the distance from ground zero to tinder of 24,500 feet.

Answer

7.21 In the same manner it is possible to calculate the distance from ground zero at which a primary ignition (i.e. an ignition due directly to the radiant heat emission and not due to fire spread) is just possible.

LAND SURFACE	HEIGHT OF BURST in Feet	VISIBILITY in Miles	MAXIMUM DISTANCE FROM GROUND ZERO AT WHICH NEWSPAPER MAY SUSTAIN SPONTANEOUS FLAMING IGNITION. (FEET). TOTAL ENERGY YIELD OF WEAPON = 5 MEGATONS — GLAZING AND WINDOW SCREEN COMBINATIONS: NONE	SINGLE WINDOW SCREEN	SINGLE PANE GLAZING	SINGLE PANE GLAZING SINGLE SCREEN	DOUBLE PANE GLAZING	DOUBLE PANE GLAZING SINGLE SCREEN	PRIMARY IGNITION
Bare of Snow	5,000	2	21,000	17,000	16,500	14,500	14,000	12,000	Probable
			23,500	21,000	20,000	19,500	19,000	17,000	Possible
Bare of Snow	30,000	2	0	0	0	0	0	0	Probable
			28,000	21,000	18,000	8,000	2,000	0	Possible
Bare of Snow	5,000	10	36,000	31,000	30,000	25,500	24,500	21,500	Probable
			50,000	45,000	43,000	38,000	36,000	31,500	Possible
Bare of Snow	30,000	10	36,000	26,500	23,000	11,000	4,500	0	Probable
			64,000	53,000	50,000	40,000	36,500	27,000	Possible
Snow Covered	5,000	10	39,000	35,000	33,500	30,000	28,000	25,000	Probable
			54,000	48,000	46,000	41,000	39,000	35,500	Possible
Snow Covered	30,000	10	35,000	26,000	21,500	10,000	0	0	Probable
			64,000	53,500	49,000	40,000	36,000	26,500	Possible
Snow Covered	5,000	50	61,000	53,000	50,000	42,000	40,000	34,000	Probable
			90,000±	80,000	76,000	65,000	61,000	54,000	Possible
Snow Covered	30,000	50	44,000	33,000	28,500	18,000	13,000	0	Probable
			82,000	68,000	62,000	49,000	45,000	34,000	Possible
Bare of Snow	0	2	16,500	15,000	14,500	13,000	12,500	11,000	Probable
			19,500	19,000	18,000	17,500	17,000	15,500	Possible
Bare of Snow	0	10	30,000	27,000	26,000	23,000	22,000	19,500	Probable
			41,000	37,500	36,000	32,000	30,000	27,500	Possible
Snow Covered	0	50	48,000	41,000	39,000	33,000	30,000	26,000	Probable
			75,000±	65,000	61,000	52,000	48,500	42,000	Possible

Figure 7.22.1 DISTANCE FROM GROUND ZERO OF A 5 MEGATON TOTAL ENERGY YIELD NUCLEAR WEAPON AT WHICH SPONTANEOUS SUSTAINED FLAMING IGNITION OF NEWSPAPER MAY RESULT UNDER VARYING CONDITIONS OF ALTITUDE OF DETONATION, LAND SURFACE COVER, VISIBILITY AND WINDOW GLAZING AND SCREENING.

If a weapon of 5 megaton total energy yield is assumed, Figure 7.16.1 shows that the lowest thermal energy at which ignition may occur is approximately 7 calories per square centimetre. Using the same trial-and-error procedure as that demonstrated in the example, a distance corresponding to this delivery may be computed. It is not difficult to see that under any given set of conditions of weapon yield, detonation altitude, weather conditions and with observed values of τ_B and τ_W, two closed boundaries may be drawn around ground zero. The inner boundary marks the limit at which sustained flaming ignition of newspaper tinder is probable and within which major fires may be expected. The outer boundary marks the limit at which ignition is possible but improbable and beyond which primary ignition is not likely to occur. The effective boundary of the zone of primary ignitions probably lies between these two contours. The limit of the zone in which major fires are likely to occur probably tends to lie closer to the inner contour than the outer contour. It is not possible to be more precise than this. However, for planning purposes it is often convenient to establish only one bounded zone to estimate the limits of the area in which primary ignitions may occur. For want of better information it is probably reasonable to settle on a boundary lying midway between the probable and possible ignition limits. In this manual this contour will be referred to as the boundary of the effective primary ignition zone. In adopting this practice it must be firmly borne in mind that some primary ignitions may occur beyond this boundary but that it lies where ignitions are likely to be sporadic. This demarcation should therefore be treated merely as a convenience.

7.22 Distances to the inner and outer ignition boundaries, from the ground zero of a 5 megaton total energy yield weapon, have been calculated and tabulated in Table 7.22.1, for various combinations of weather conditions, detonation altitudes, ground covers and glazing combinations. Other factors being equal, it may be seen that the distance at which ignition may occur depends heavily on weather conditions. By contrast, it is interesting to note that air attacks made during World War II with conventional incendiary weapons during rainstorms were only slightly less effective in causing fires than attacks made in good weather. Presumably, the dependence on meteorological conditions for estimating the fire effects of nuclear weapons poses a number of problems to the military planner. For, he may not be in a position where he can wait for weather suitable for producing maximum fire damage. Nevertheless, Table 7.22.1 shows that under a wide variety of conditions a considerable amount of damage may be achieved.

SECTION 8

CONFLAGRATION AND SPATIAL SEPARATION

8.1 It is not easy to assess the risk of a major fire resulting from the burning of paper inside a building. Wide variations in the array and in the properties of combustible contents that exist even in similar types of buildings preclude the formulation of simple rules for fire spread. However, under nuclear attack conditions, it is probably safe to assume that a significant number of buildings at and near the boundary of the probable primary ignition zone, as defined by the methods of Section 7.21, will suffer major damage due to fire.

8.2 It has been long recognized that a well-developed fire in one building may cause the ignition of combustibles in nearby properties. Therefore, it is not possible to assess fire losses merely by estimating the number of buildings in which primary ignitions may take place. Indeed, near the boundary of the effective primary ignition zone, the damage caused by conflagration (i.e. the spread of fire from one building to other buildings) is likely to exceed that sustained by buildings in which untended primary ignitions have occurred. The important issue is, whether or not conflagration will spread outwards to damage substantially large areas that may lie beyond the primary ignition zone.

8.3 Studies of fire in buildings have shown that there are several mechanisms by which conflagration may occur. Briefly, these are by the flow of burning liquids from one building to another; by the radiant thermal emission from a burning building; by the impingement of flames and hot gases; and by flying brands. The flow of burning liquids is likely to be confined to commerical and industrial areas where inflammable fluids, such as paint and alcohol, may be stored in large quantities. In residential areas, the risk is not likely to be significant. Compared to the large areas of an urban target that may incur numerous major fires following a nuclear attack, the areas likely to be damaged by burning liquids will be only of local and secondary importance.

8.4 On the other hand, the conflagration hazard due to radiant emission from a burning building is likely to be of the greatest significance. This may be realized in a qualitative sense when it is remembered that temperatures in well-developed fires in residential buildings may approach and sometime exceed 1,000°C. Under such conditions, windows and other openings in exterior walls behave as highly efficient (i.e. almost black-body) thermal emitters analogous to small fireball surfaces. Naturally, if the emitted heat impinges at a sufficient rate and in sufficient quantity upon combustibles in nearby property there

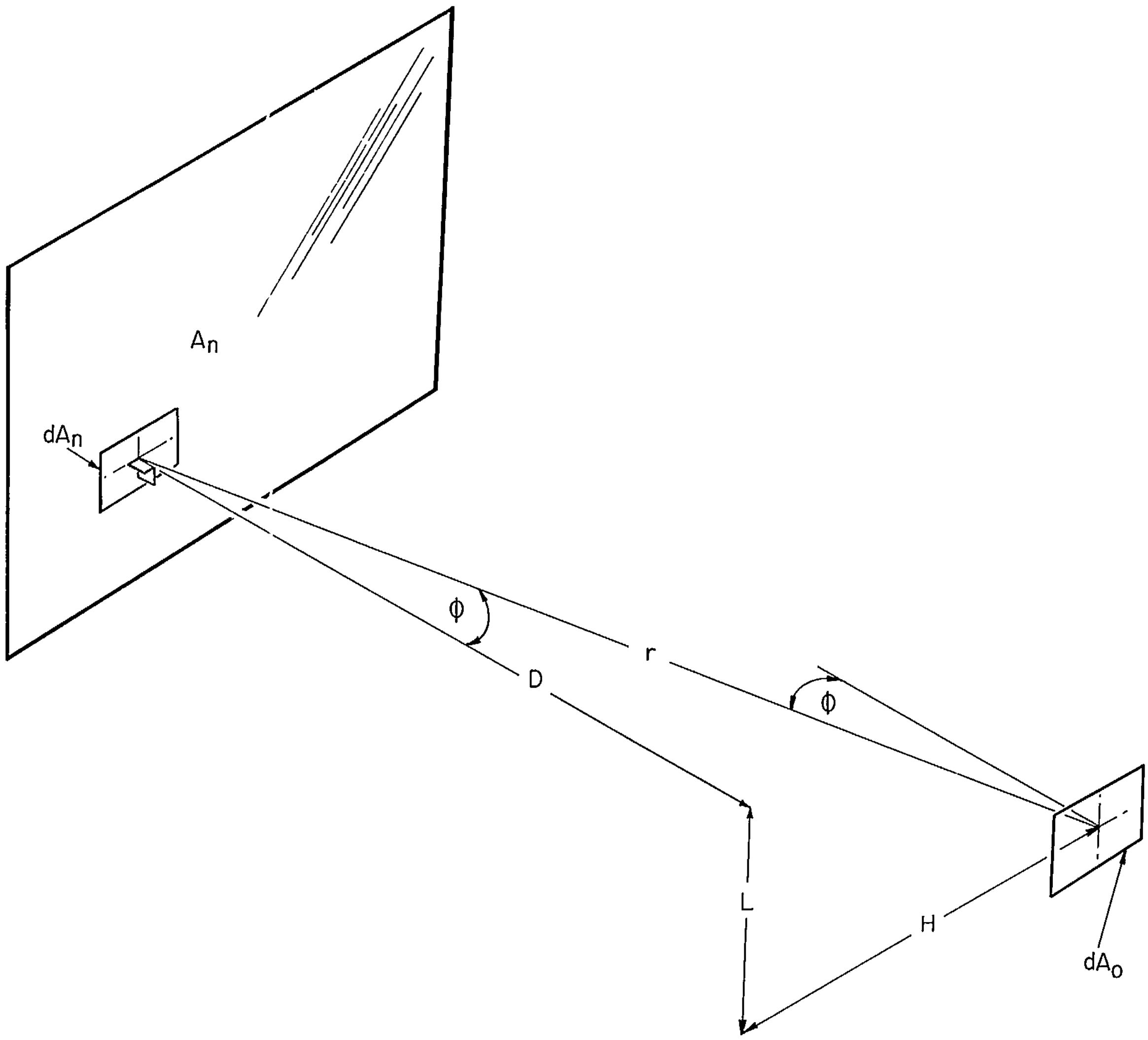


FIG. 8.5.1 GEOMETRICAL RELATIONSHIPS BETWEEN RADIATING AND ABSORBING SURFACES.

is a likelihood that ignition will result. It is not necessarily correct to assume that only the exterior wall openings act as plane heat sources, as it is probable that heat may also be emitted from the wall faces themselves. For example, the contribution made by walls lined with a combustible wallboard may be quite significant. Nevertheless, it is customary to assume that only the wall openings act as radiators.

8.5 The heat impinging on a small elemental plane of area dA_o from a number of parallel plane source radiators may be derived from the relation given in Equation 8.5.1. An explanatory diagram of the geometry used in this equation is given in Figure 8.5.1.

$$P = \sum_{1}^{N} I_n \int_{A_n} \frac{\cos^2 \phi \, dA_n}{r^2} \qquad - 8.5.1$$

where P = thermal power delivered to the small elemental plane area dA_o, in calories. cm^{-2}. sec^{-1}

I_n = intensity of radiant heat emitted from a small element dA_n, of the plane source of area A_n, in calories. cm^{-2}. sec^{-1}.

ϕ = angle between the normal to elemental emitter surface, dA_n, and a line joining the element with the receiver dA_o

r = distance between the elements dA_o and dA_n in any unit of length (e.g. feet, centimetres, etc).

N = number of emitting surfaces in which the nth is of area A_n

A_n = area of the nth plane heat source emitter, in units consistent with the measurement of r

A number of simplifications may be applied to Equation 8.5.1 that render it into a more convenient and practical form. Without introducing significant errors, it is usually possible to assume an 'average' value of r for the area, A_n, by taking it to be the distance from the centre of this area to the receiving element dA_o. Equation 8.5.1 may now be rewritten in the form of Equation 8.5.2.

F	CONDITION OF WOODEN FRAME
0.067	Paint blistered.
0.067	Paint blistered, little charring.
0.081	Surface charring.
0.093	Burned.
0.112	Burned.

Table 8.6.1 DAMAGE RELATED TO CONFIGURATION FACTOR

$$\frac{P}{I_n} = \sum_{1}^{N} \frac{\cos^2 \phi A_n}{r_n^{\,2}} \qquad - 8.5.2$$

where r_n = distance from the centre of the emitter of area A_n to the receiver element of area dA_o

Also, I_n may be assumed to be constant for all wall-opening emitter sources in a burning building if the temperatures throughout the building are substantially uniform. Furthermore, for any specified type of ignition, the thermal power, P, has a fixed value. For example, spontaneous flaming ignition takes place in many common cellulosic solids when P = 0.8 calories per square centimetre per second. Therefore, a prediction of ignition may be made from the purely geometrical terms on the right hand side of Equation 8.5.2. This term

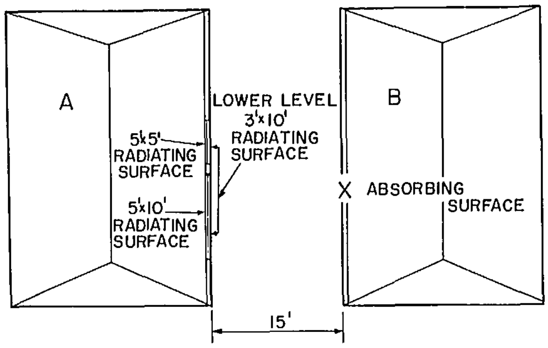
$$\sum_{1}^{N} \frac{\cos^2\phi\, A_n}{r_n^{\,2}}$$

is usually known as the configuration factor and is sometime symbolized by the letter, F.

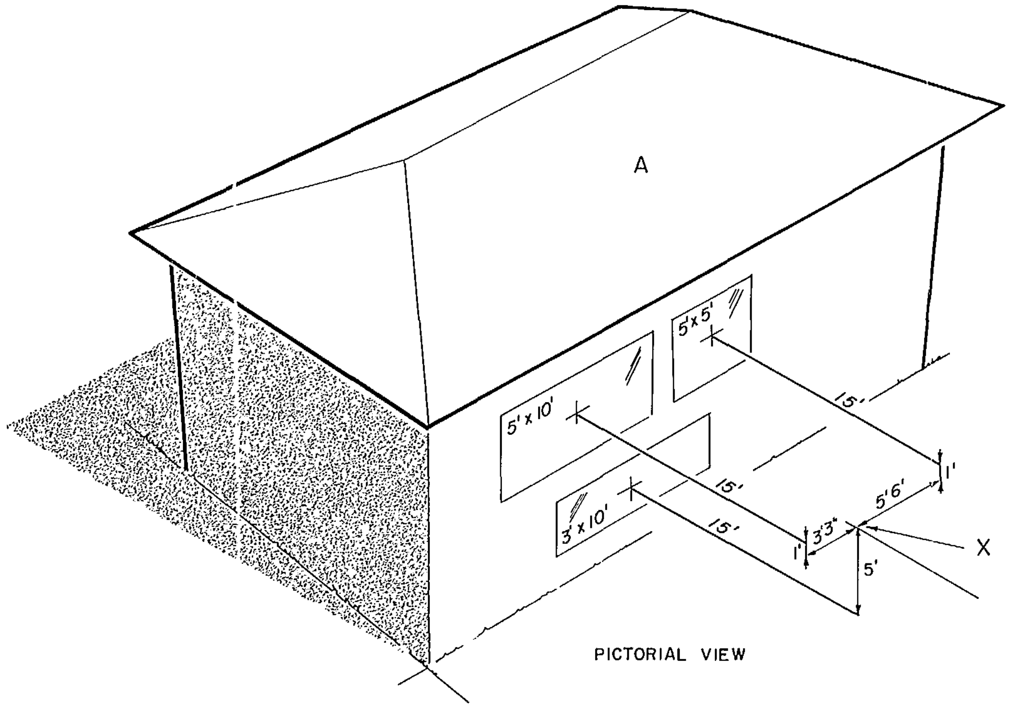
8.6 Bevan and Webster[12] have made analyses of building fires to determine values of configuration factors consistent with thermal damage. A short table of some of their findings is reproduced in Table 8.6.1. It will be noted that charring of wood begins when the configuration factor is approximately 0.067 and burning commences when the factor is approximately 0.093. These values may be used to predict the likelihood of conflagration occurring due to radiation. This may best be shown by an example.

8.7 Example of Conflagration due to Radiation from a Building Fire

Given Buildings A and B are located as shown in Figure 8.7.1. A well-developed fire occurs in building A. The configuration of windows and the appropriate dimensions are given in Figure 8.7.1. It is required to find the configuration factor at point 'X' on a wooden door frame in building B.



PLAN VIEW



PICTORIAL VIEW

FIG. 8.7.1. ILLUSTRATION OF GEOMETRICAL RELATIONSHIP BETWEEN RADIATING SURFACES AND ABSORBING SURFACE.

Solution   From Equation 8.5.2.

$$F = \text{Configuration factor} = \sum_{1}^{N} \frac{\cos^2 \phi A_n}{r_n^2}$$

For Window No. 1

$$A_1 = 5' \times 10' = 50 \text{ sq. feet}$$

$$\cos^2 \phi = \frac{15.0^2}{(15.0^2 + 1.0^2 + 3.25^2)}$$

$$r^2 = (15.0^2 + 1.0^2 + 3.25^2)$$

$$\therefore \quad F_1 = \frac{50 \times 15.0^2}{(15.0^2 + 1.0^2 + 3.25^2)^2}$$

$$= 0.200$$

Similarly

$$F_2 = \frac{25.0 \times 15.0^2}{(15.0^2 + 1.0^2 + 5.5^2)^2}$$

$$= 0.085$$

and

$$F_3 = \frac{10.0' \times 3.0' \times 15.0^2}{(15.0^2 + 5.0^2)^2}$$

$$= 0.108$$

$$\therefore \sum_{1}^{3} F = 0.200 + 0.085 + 0.108$$

$$= 0.393$$

From Table 8.6.1, it is obvious that the door frame at point X is very likely to burn.

Answer

8.8 The question may arise of the method of computing a configuration factor when a part of an external wall collapses. In this case, the surface area of the opening behaves as a window and its effect may be determined in the same manner as was shown in the foregoing example in Section 8.7. If the collapse involves a large area of the wall, it is often better to divide the area into smaller sections and treat each section as a window. When the configuration factor of each part has been calculated, the results may be added together to give a configuration factor for the whole area.

8.9 It is interesting to note from the example in Section 8.7 that conflagration may well result from radiant heat when a gap width of 15 feet exists between buildings (which, in this case, are intended to portray those of a residential type). As the distance between many modern Canadian homes in suburban areas is of this order, the risk of conflagration is obviously great. Presumably, the present laws fixing minimum separation between buildings are based on the assumption that fire-fighting appliances will arrive before conflagration develops. Obviously, the risk decreases as the gap increases but for reasons of economy in land and municipal services it is not always possible to provide a more substantial margin of safety. In the event of nuclear attack, when fire appliances may not be available, it may be safely assumed that fire-spreads from one building to another may account for a great deal of fire damage.

8.10 Unfortunately, conflagration risks do not end with radiant heating. It is also possible that flames or hot gases may project far enough from a building fire to contact combustible materials in adjoining buildings. Usually, this occurs when the gap separating buildings is less than 20 feet, although it is conceivable that the same effect may be achieved at greater distances under some wind conditions. At the present state of knowledge, it is not possible to predict the effect of flames and hot gases. In the same way, it is impossible to predict the conflagration effect of flying brands.

8.11 All the vehicles of propagating fire-spreads between buildings are affected by wind but, probably, none so obviously as flying brands. It has been noticed during building fires that the radiation, flame and hot gas mechanisms of conflagration are also sensitive to changes in wind speed and direction. However, there is no available method of accurately predicting their effects. Nevertheless, experience has shown that fires of moderate proportions may be controlled by prompt and determined action provided the wind velocity does not exceed 15 miles per hour. As the velocity is increased to 30 miles per hour, the rate of fire spread greatly increases. At this higher speed, a minor blaze involving only a few buildings may place all down-wind structures in grave jeopardy.

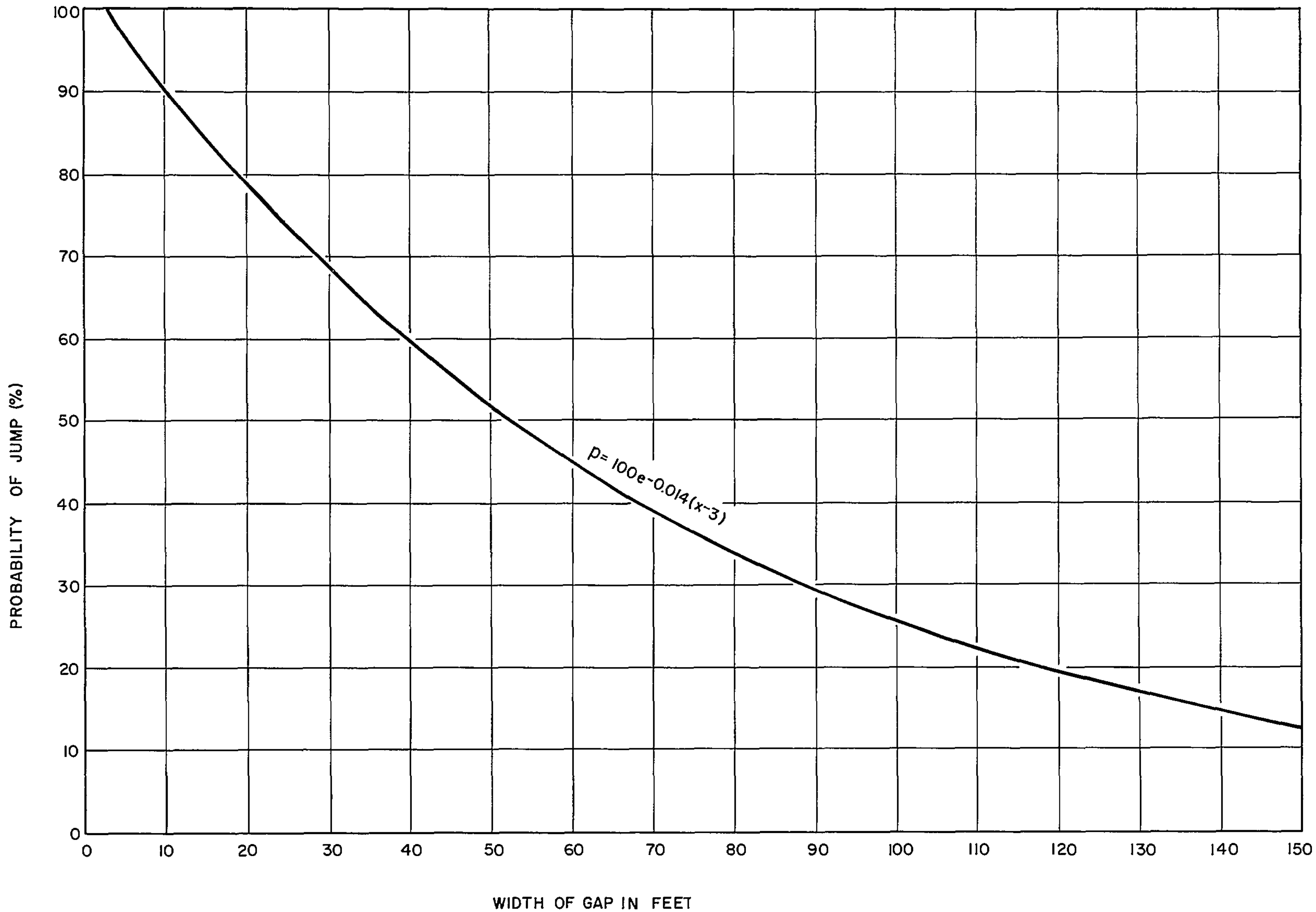


FIG. 8.12.1. PROBABILITY THAT FIRE WILL JUMP A GAP (WORLD WAR II DERIVATION) $p = e^{-0.014(x-3)}$ p = PROBABILITY, x = GAP WIDTH IN FEET

8.12 Although it is probable that, under most circumstances, radiant heat from building fires causes more conflagrations, the other methods of fire spread may not be ignored. However, as there are no methods of assessing their relative importance it is necessary that an empirical relationship based on experience be used. Such an expression was derived from a study of fire damage in German and Japanese cities that sustained aerial attack during World War II. This relationship, which is given in Equation 8.12.1[13], and presented in Figure 8.12.1,

$$p = 100e^{-0.014(x-3)} \qquad - 8.12.1$$

where p = the percentage possibility of fire jumping a gap x feet wide, and producing a conflagration

x = Width of gap, in feet

attempts to give an estimate of fire jumping a gap of known width. As there cannot possibly be one simple equation that is adequate to describe all sizes and types of buildings and their contents, it may be assumed that Equation 8.12.1 is no more than a useful guide. However, it appears to be the best information available and it has the undoubted advantage of being derived from field experience and measurement.

8.13 It is often valuable to assess the amount of building property that may be substantially destroyed by fire within the confines of a city block. A study made in Japanese residential areas following fire attack showed that the amount of damage was related to building density, that is, to the fraction of ground covered by buildings. This study shows the approximate relationship given in Equation 8.13.1[13] to hold true. It may be found from this expression that when the building density is 59% (i.e. B = 0.59), total burnout results. Unfortunately, equivalent results

$$b_e = 1.88\,B^{1.2} \qquad - 8.13.1$$

where b_e = fraction of building burned

and B = fraction of area of block covered by buildings.

are not available from German experience that may be more closely related to Canadian conditions. Nevertheless, Equation 8.13.1 may probably be used as a reasonable approximation in the absence of better information.

SECTION 9

MASS FIRES[14]

9.1 A few of the many air attacks made during World War II against German and Japanese cities resulted in massive fires of unusual violence and destructiveness. In these cases, the effects showed that large numbers of separate building fires had merged into groups of considerable size. That is, individual building fires lost their identities by joining with adjacent fires and became merely contributors to a mass fire. As merging progressed and the sizes of the groups increased, the blazes burned more fiercely. This growth in violence is attributable to local weather conditions that mass fires themselves generate. Usually, this involves the creation of winds that are induced to blow towards the fire. These promote further merging and intensify the rate of burning of combustibles. Naturally, a strengthening of the imposed weather system results and the cycle is repeated until the supply of fuels is exhausted. However, the effect of the meteorological conditions existing prior to attack may have a strong influence on the form and behaviour of mass fires. This is best illustrated by examples.

9.2 In 1943 an air attack on the German city of Hamburg produced a mass fire of such severity that approximately half of the half-million dwelling units in the city was destroyed and about 60,000 people were killed. The main assault, in which a great weight of weapons was dropped on the target, was delivered quickly with the result that the available defences were overwhelmed. Conventional incendiary and high explosive weapons were employed, the former being preponderant and the more important. Approximately one half hour after the attack was launched, two out of three buildings in an area of 4-1/2 square miles were ablaze and general fires were started over an area of approximately 17 square miles. Within an hour,merging of the blazes in the smaller area was well advanced and the resulting mass fire burned with increasing ferocity for several hours until the remaining fuels were insufficient to maintain a further increase in the rate of burning.

9.3 Hamburg suffered what is now often termed a fire-storm. This is usually defined as a stationary mass fire, covering a large area, in which merging is well advanced or complete and which generates strong local winds that are directed towards the fire from all sides. These winds confine the fire-storm and prevent its spread but they also replenish the supply of oxygen and intensify the rate of burning. Prior to the assault there had been a prolonged heat-wave in the area. Winds were light and it is estimated that surface temperatures in some districts, which were to suffer greatly during the attacks, may have been as high as 100°F. It is believed that the relative humidity

was generally low. Thus, the available solid fuels, being dry, were probably prone to ignite readily. When a mass fire was formed and merging was well advanced, a column of burning gases more than 2-1/2 miles high and 1-1/2 miles in diameter rose from the fire-storm area. Large convection currents of ascending and descending air were formed and horizontal winds, that strengthened to hurricane force at the perimeter, were generated. These induced air currents, which are sometimes termed fire-winds, blew from all sides towards the fire. Due to the large area involved, the effect of the rotation of the earth caused the fire-winds to proceed on spiral rather than straight routes towards the centre. The depth of penetration into the area beyond the perimeter is thought to have been about 1/2 mile. Not only did they replenish the supply of oxygen for combustion but they also acted like the air from a bellows upon a forge. It has been estimated that the heat in the fire-storm area may have been sufficiently intense to cause the temperature in streets flanked by tall buildings to rise as high as 1,400°F.

9.4 The fire-storms created in World War II had many common features. All were remarkable for the great damage and the heavy casualties that they caused. From the evidence it seems clear that the prerequisites for their occurrence are the production over a large area, where a plentiful supply of solid fuels exists, of numerous ignitions within a short period. Furthermore, it appears to be essential that the wind prevailing prior to attack should be no more than light, so that it neither prevents the onset of a fire-storm nor permits it to grow beyond its original size or to translate from its original position.

9.5 Despite their ferocity, it is not necessarily true that fire-storms are more disasterous than mass fires which are propelled by prevailing winds. An aerial fire attack on Tokyo in March 1945 was made while a wind of approximately 25 miles per hour was blowing in the target area. Although it effectively prevented the establishment of a characteristically stationary fire-storm, the wind drove a mass fire through the city and substantially destroyed all structure in an area of 15 square miles. The loss of life exceeded that suffered at Hamburg. The evidence shows that fire-merging was well advanced and fire-winds, comparable to, but not as strong as those induced into the fire-storm area in Hamburg, were established. The assaults on both cities had much in common. They were launched against targets where plentiful supplies of solid fuels in dense array existed, and both cities were subjected to intense attack with predominantly incendiary weapons. The only significant difference lay in the state of the wind prior to the attack.

9.6 Forest wildfires sometimes produce conditions resembling those of urban mass fires. It is possible that meteorological effects may play a more significant part in violent forest fires than they do in mass fires started in attacks on wartime targets. For example, one authority[15] has suggested that the behaviour of a wildfire, which occurred in Arizona in 1956, may be related to the presence of high-altitude winds of great velocity known as jet streams. These winds tend to produce weather disturbances that sometimes lead to intense local squalls. In this case the air immediately above the blaze was found to rotate counterclockwise, in the downward direction, in a spiral, with its axis horizontal, to form a Benard cell. The diameter of this convection system was approximately 5,000 feet, and one complete rotation was executed in a horizontal distance of approximately 6,000 feet. Apart from showering the lateral and down-wind areas with sparks and flying brands, the spiralling system appears to have produced the effect of reducing the relative humidity of ground level, near the scene of the wildfire, from 20 percent to 4 percent. Naturally, the consequent drying of the forest fuels made them prone to ignite readily. This wildfire appears to have had features in common with both the Hamburg and Tokyo fires. As at Hamburg, the solid combustibles were subjected to drying before ignition; in the manner of the Tokyo fire, the blaze was driven before a wind. In all three cases there existed a plentiful supply of closely spaced fuel.

9.7 Putnam and Speich[16] have simulated mass fires with groups of buoyancy - controlled flames using gaseous fuels. They found that when the spacing between flames was decreased there was an increasing tendency for them to interact. The flame-heads leaned towards each other and the flames lengthened until a critically small spacing was attained when a complete merging occurred. (The lengthening was attributed to a mutual shielding effect that partially blocked the flow of induced air to the jets. To provide an equivalent flame surface to which the air has access, presumably it is necessary for the jet to extend to replace the surface lost by shielding. Furthermore, there appears to be an effect by which flames aspirate each other and provide a condition of mutual support). For any array of multiple sources, the fuel-flow rate, the number of jets and the shape of the array all seemed to have a marked effect on flame-merging. However, for a given shape of array and under fixed conditions of spacing and fuel-flow rate, it does not appear to matter how sources are arranged within the pattern. Whether the flames are uniformly distributed or distributed around the perimeter of the pattern, the degree of merging remains constant. Putnam and Speich also investigated the air movements associated with flame groups. They found that a straight, or line array (i.e. roughly comparable to the Tokyo conditions where the blaze was described as a "wall of fire" in contrast to an "area of fire" in Hamburg) induces air from both sides of the line, while an area grouping is supplied by air flowing only towards

the perimeter of the array. Further experiments were conducted with air currents applied to flame groups. This was intended to simulate the effects of prevailing winds on mass fires. In a manner to be expected, the flames tilted in response to the air flow. In line arrays, the flame lengths shortened under increasing wind speeds until a constant length of approximately 0.7 of the unblown length was attained. Thus, although the flame tilting in a mass fire that is advancing under the influence of a wind may increase the risk of ignition to fuels lying in its path, it is possible that the shortening of the flame may diminish the hazard to some extent.

9.8 It is obvious that a nuclear weapon is potentially capable of producing mass fires in an urban target. At Hiroshima, the site of the first nuclear attack, a fire-storm was produced. At Nagasaki, the site of the second attack, numerous small mass fires were started but none was comparable to those that occurred in Hiroshima, Hamburg or Tokyo. In this case the geography of the city prevented the production of ignitions over a sufficiently large part of the target to permit the development of large mass fires.

9.9 The probability of a fire-storm occurring has been related to building density and coverage (i.e. the ratio, expressed as a percentage, of projected roof area to total ground area within a selected zone, and the amount of ground occupied by each density group). Three broad categories have been proposed. The first is where the building density lies in the range 0 percent to 5 percent. In this category it is not expected that fire will spread beyond the building in which it originates. Furthermore, if the ground area covered in this density group is large, it may provide a substantial fire-break. The second applies where building density lies in the range of 6 percent to 20 percent. Areas falling into this group may be expected to suffer to some extent from conflagration effects, but large mass fires are not likely to occur. The last category comprises regions where building density exceeds 20 percent and the corresponding ground coverage exceeds 1 square mile. In this case, fire-storms may be expected to occur if meteorological conditions permit their establishment.

SECTION 10

THE EFFECTS OF FIRES ON STRUCTURAL MATERIALS

10.1 For some time following a nuclear attack, it is likely that normally acceptable standards of housing may cease to apply. As it is improbable that all buildings in an attacked city will suffer an equal amount of damage, those that have suffered least may, of necessity, be required to shelter people who have been temporarily rendered homeless. This raises the issue of which buildings may be expected to survive fire damage with the least structural defect. The answer lies partly in the response of construction materials to the effects of the high temperatures often associated with building fires. Due to the wide variety in the mode and quantity in which these materials are employed, it is very difficult to categorize buildings into types according to their resistivity to fire. Indeed, it is probably safe to say that every building must be studied with regard to its construction, its contents and the manner in which it is divided, before a reliable assessment of its chance of surviving a fire may be made. Naturally, this would be a major task involving a great deal of the time of those who are experienced in these matters. Despite this difficulty, a very rough estimate of a building's state after a fire may be obtained from a knowledge of the materials of its construction. For this reason, the remainder of this section is devoted to brief notes on the behaviour of some of the more common structural materials in a fire. These materials are discussed in no particular order.

10.2 Structural Steelwork - Although structural steelwork is incombustible, it is not fire-resistant. At elevated temperatures it may be expected to deform and undergo changes in its strength and elastic properties. Figure 10.2.1[17] shows the manner in which ultimate compressive and tensile stress values change as temperature is raised. It may be seen that in the initial stages the strength increases; but, at temperatures which may be encountered in well-developed building fires (say, about 1,800°F), a marked loss of strength is evident. This reduction in capacity to sustain loads may induce large deformations or collapse of a building. Quite apart from changes in strength, there is also a decrease in elastic modulus (i.e. Young's modulus of elasticity) with increasing temperature. The approximate relationship between modulus and temperature, in the range of 200°F to 1,300°F, is given in Equation 10.2.1.[18] Due to the fact that the buckling strength of long, axially-loaded struts and columns is directly proportional to elastic modulus, it may be concluded that there is a danger of column failure, caused by high temperatures attained in building fires, inducing the collapse of supported floors and roofs. For example,

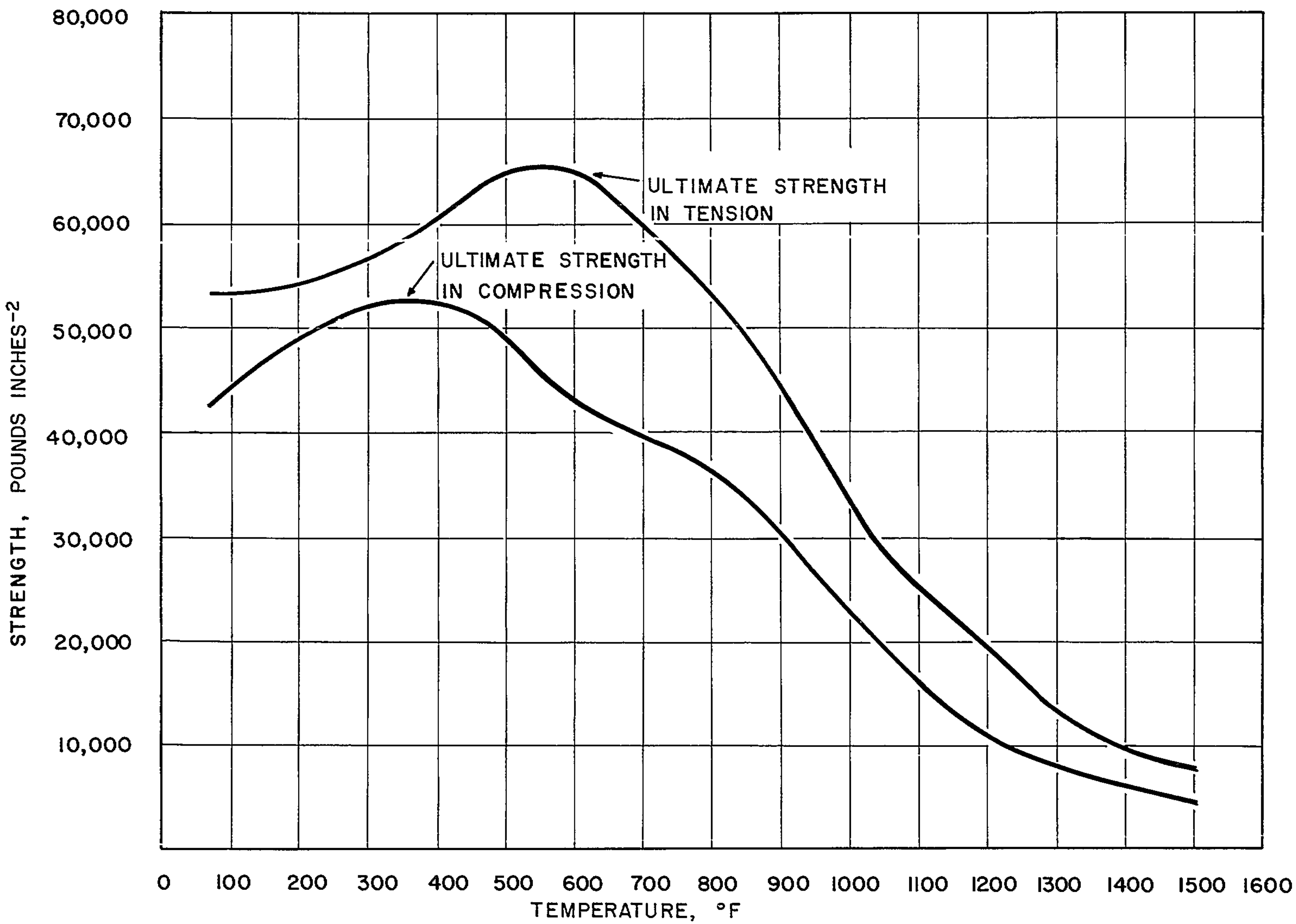


FIG. 10.2.1 STRENGTH OF STRUCTURAL STEEL UNDER FIRE EXPOSURE.

$$E = 32{,}400{,}000 - 17{,}000\,T \qquad - 10.2.1$$

where E = initial modulus of elasticity in pounds per square inch

and T = temperature in degrees Fah.

if it is assumed that the modulus for steel is 32,400,000 pounds per square inch at normal room temperature, from Equation 10.2.1, it is evidently only approximately 10,300,000 pounds per square inch at 1,300^{o}F. This represents a decrease by a factor of approximately 3.1 in modulus, and therefore, in capacity to resist buckling. A diminution of this order is often sufficient to produce large deformations or collapse in heavily loaded members subjected to a fire. Naturally, these effects have been long recognized, and, in many cases, structural steelwork is given some protection to delay or to prevent catastrophic failure.

10.3 Aluminum Alloys - Structural aluminum alloys have a tendency to melt and lose strength at fairly low temperatures. In the main, they do not behave well in fires. Curves of ultimate tensile strength of some selected alloys against temperature are given in Figure 10.3.1 [17]. It may be noticed that sheet aluminum alloys tend to behave better than the structural alloys.

10.4 Cast Iron - Cast iron structural members, particularly columns, were used extensively in older buildings and, in the main, they performed rather better than structural steel under heat. However, cast iron is subject to cracking and breaking when suddenly cooled as, for example, when water streams from hoses are applied. This has produced some dangerous structural failures. The use of cast iron in structures is now quite limited.

10.5 Brickwork - The melting point of clay bricks appears to be in the range of 2,100^{o}F to 2,500^{o}F. Unusually fierce fires have caused superficial fusing but, in most building fires, brickwork survives very well. However, it sometimes occurs that the expansion of structural framing members subjected to high temperature pushes external walls outwards and causes them to collapse. The risk of this occurring depends on the stiffness of the wall.

10.6 Reinforced Concrete - The flexural strength of concrete made with either normal Portland or high alumina cements decreases upon exposure to high temperatures. The compressive strength of concrete, made with gravel, sandstone or expanded slag aggregates, may tend to exceed that obtained at normal room temperature for a

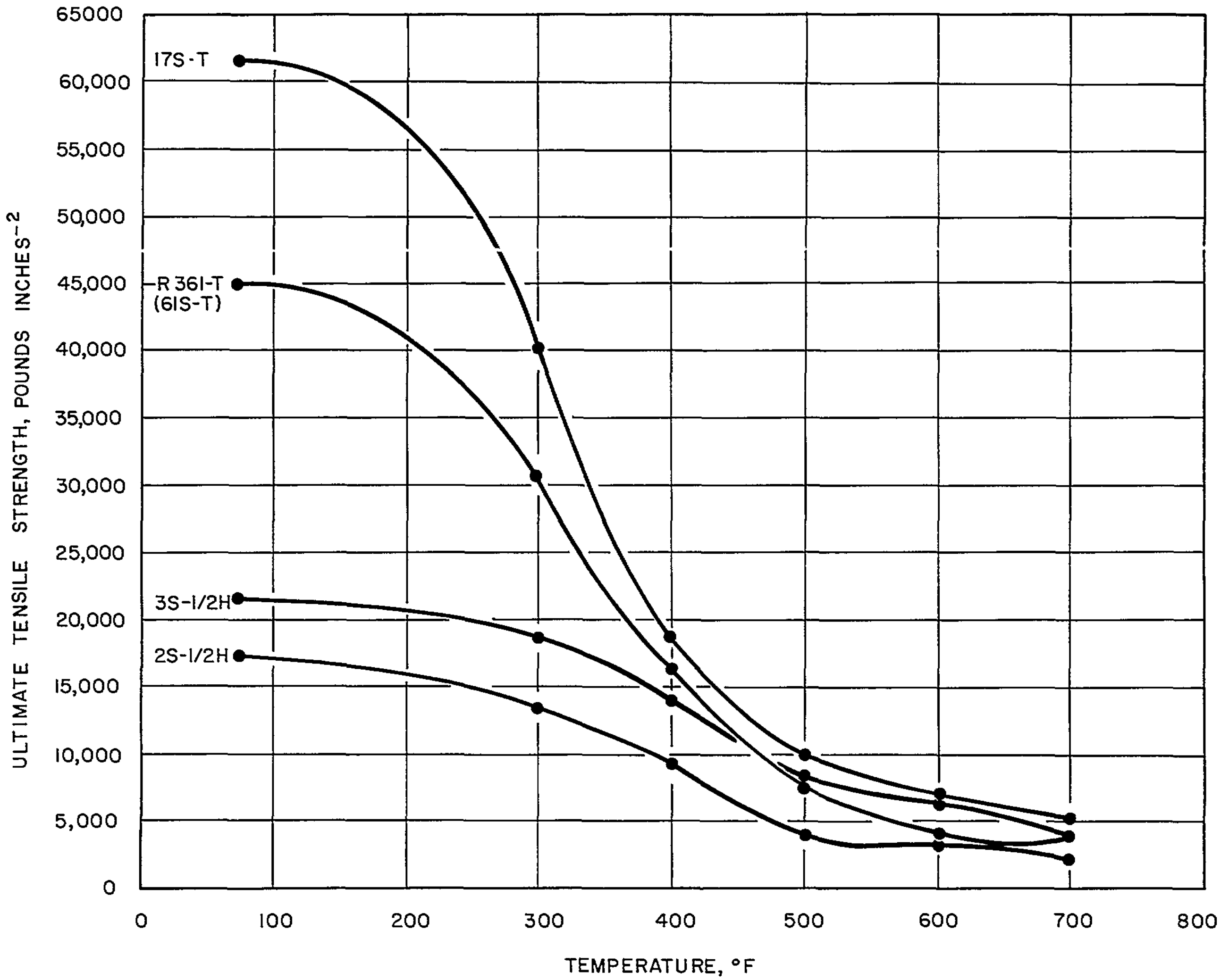


FIG. 10.3.1 THE EFFECT OF TEMPERATURE ON THE STRENGTH OF WROUGHT ALUMINUM ALLOYS. 17S-T AND 61S-T ARE TYPICAL STRUCTURAL ALLOYS; 3S-1/2H AND 2S-1/2 ARE TYPICAL SHEET ALUMINUM ALLOYS. THE CURVE SHOWS TEST RESULTS AFTER PROLONGED HEATING. CURVES BETWEEN DOTS ARE ASSUMED.

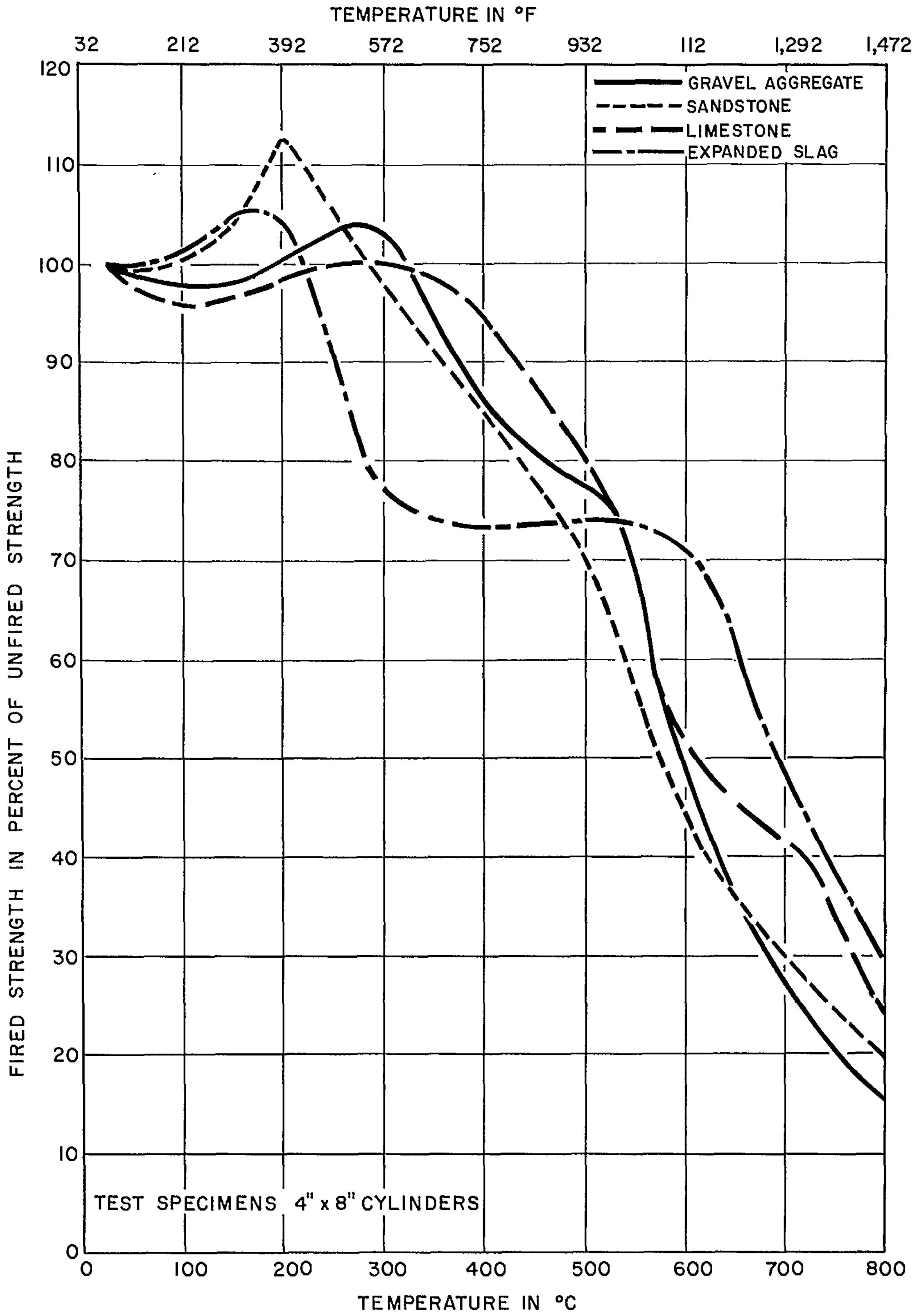


FIG. 10.6.1 LOSS OF COMPRESSIVE STRENGTH IN PORTLAND CEMENT CONCRETE SUBJECTED TO HEAT AND TESTED AT ROOM TEMPERATURE. (ADAPTED FROM "EFFECT OF HIGH TEMPERATURES ON CONCRETE INCORPORATING DIFFERENT AGGREGATES" BY N.G. ZOLDNERS).

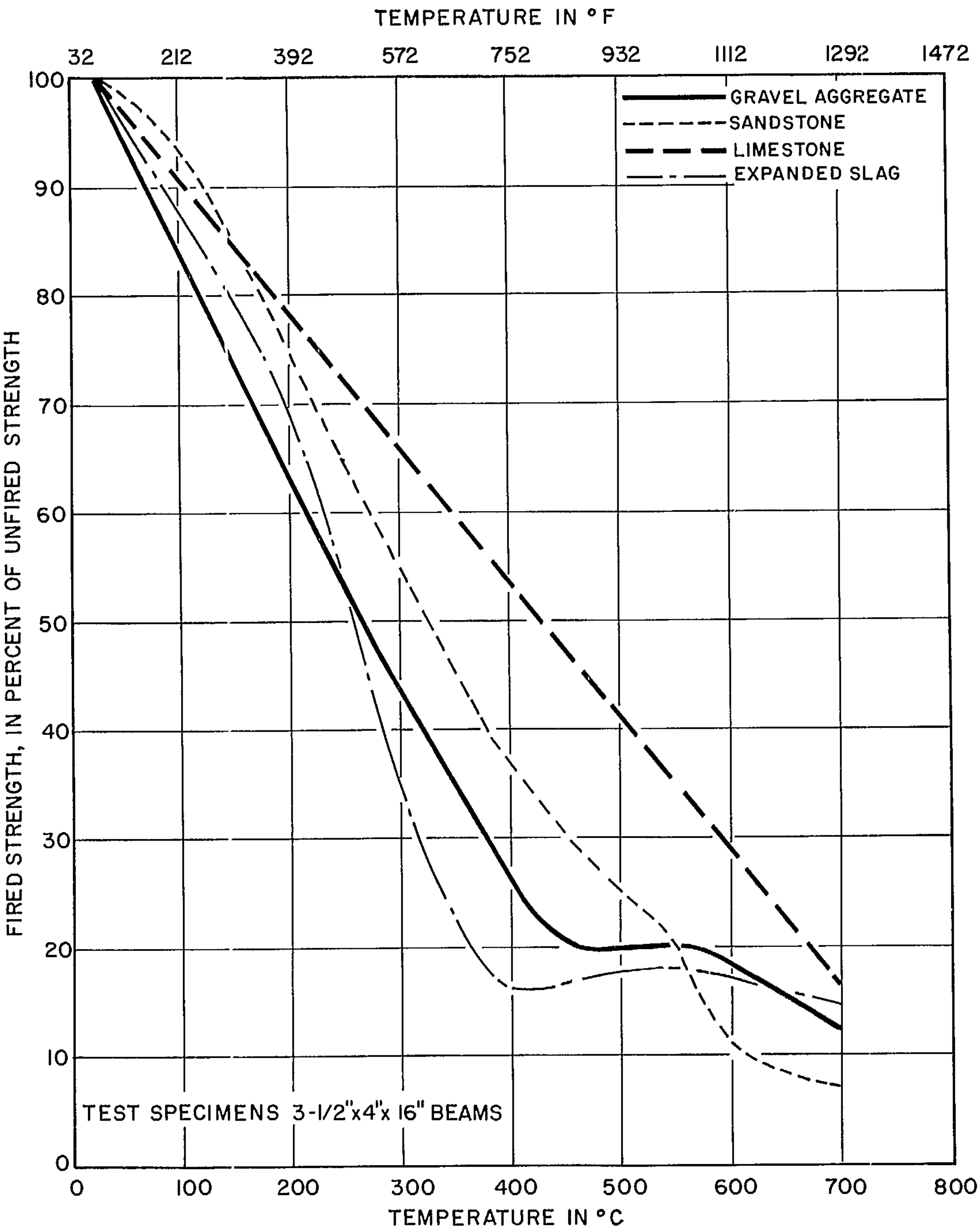


FIG. 10.6.2 LOSS OF FLEXURAL STRENGTH IN PORTLAND CEMENT CONCRETE SUBJECTED TO HEAT AND TESTED AT ROOM TEMPERATURE (ADAPTED FROM "EFFECT OF HIGH TEMPERATURES ON CONCRETE INCORPORATING DIFFERENT AGGREGATES" BY N.G. ZOLDNERS).

relatively small increase in temperature. However, under the conditions normally imposed by a well-developed fire, there is a marked decrease in strength. The results of tests conducted by Zoldners [19] on Portland cement concretes for a variety of aggregates have been reproduced in Figures 10.6.1 and 10.6.2. At first glance the data given in these figures do not appear to be compatible with the usually good fire-resistant qualities associated with concrete. The reason is that Zoldners' tests were conducted on small specimens which were heated for a substantial period, so that all of the concrete attained a high temperature. Usually, concrete structural members are massive as compared with the sizes of the test pieces with the result that, in many building fires, the cores of the members remain quite cool, and therefore strong, even though the surfaces may have deteriorated. This unevenness of temperature sometimes leads to a spalling of the surfaces of a concrete member due either to thermal stress failure or failure in aggregates and cement paste. If this occurs, a new surface is exposed to fire and the penetration of heat into a member may increase. Usually, a more serious effect is that reinforcing steel may be exposed to heat with the result that it loses some of its ability to sustain stress (see Section 10.2) and structural collapse may ensue. An interesting example of a fire resistance test made on a 5-inch thick solid-concrete floor slab under controlled conditions, has been given in the literature.[20] The temperature of the exposed soffit rose to a maximum of 1,900°F. The temperature attained after two hours of fire exposure at distances of 1 inch and 2-1/2 inches from the soffit were only 1,060°F and 670°F respectively. This example shows, in a rather striking manner, the resistive effect of mass in concrete structures. In contrast, unprotected structural steel is usually composed of thin flanges and webs through which heat may be dispersed in a fairly uniform manner. Coupled with this is the fact that the thermal conductivity of steel is considerably higher than that of the more common concretes, so that heat passes more quickly through steel than through concrete. The result is that incipient collapse usually occurs sooner in unprotected structural steel frames than in concrete frames under equal fire conditions.

10.7 Prestressed Concrete - The behaviour of the concrete in prestressed concrete structures is similar to that described in Section 10.6. However, under equal loading conditions, prestressed concrete members tend to be less massive than corresponding reinforced concrete members. This implies that the percentage of concrete affected by fire tends to be higher in the former than the latter. Usually, a more serious result of fire occurs when the high-tensile steel stressing rods (or wires) are subjected to high temperatures that may cause a differential elongation between concrete and rods and a consequent

loss of prestress. There is also a possibility that some of the qualities required of the steel to sustain tension continuously over long periods, may be lost due to changes in its metallurgical structure. Furthermore, prestressed concrete beams are not usually employed in continuous building frames, where all the beams and columns act together as a unit, but, rather, tend to be used as units with simple support. Structural continuity noticeably improves the performance of a building in which a fire has occurred so that prestressed concrete units suffer some disability in this respect. Despite these shortcomings it behaves well in fires especially when the designer has taken care to ensure that an adequate cover is provided for the steel rods.

10.8 Timber - The performance of timber in building fires depends greatly upon the sizes of the members. Experience has shown that structural members of large cross-sectional dimensions behave remarkably well while small units, such as boards, purlins and unprotected studs may be completely consumed. Standard fire tests conducted in the United Kingdom indicate that for solid timber and plywoods of medium density, soft-woods and hard-woods, the rate of charring is approximately 1/40th of an inch per minute, although some decrease may be achieved by impregnating wood with fire retardant salts. The ability of members of large cross-section to survive fire depends on the low thermal conductivity of wood. Obviously charred wood has no structural value, but probably not more than 1/4 inch beyond the depth of char, it is likely that the strength of the wood will remain substantially unimpaired. Naturally, if a member is not subjected to fire for too long a period, sufficient undamaged wood may remain to sustain applied loads without failure. The endurance period of timber beams to standard fire tests has indicated a relationship of the form given in Equation 10.8.1.

$$r^{0.5} = 1/2\,(1 - T\,s^{0.5})\left(1 - \frac{T}{2s^{0.5}}\right)^2 \qquad - 10.8.1$$

where r = ratio of working stress to ultimate stress

s = ratio of beam depth to width

$T = \dfrac{t}{20a^{0.5}}$

t = fire endurance in minutes

a = cross-sectional area of beam in square inches

While this equation does not include all of the factors that affect performance in a fire (such as moisture distribution in the member and whether or not edges have been chamfered), it does indicate the dependence on size, shape and strength on the ability of timber to survive a fire. In the main, the behaviour of wooden floors and partitions depends on the joints. Where tongue-and-groove boards are employed, only the thickness of the tongue prevents the passage of flame after the boards have shrunk due to heat. Plain edge boarding has little value in resisting flame-spread.

10.9 Although the discussion has centred on structural members, there are many materials used in the construction of a building that may enhance or diminish the effects of a fire. These are too numerous to detail, but particular mention should probably be made of the fire-retarding effects of gypsum and lime plasters and asbestos. However, for a fuller account the reader is referred to "Fire Resistance Ratings, 1961", Supplement No. 2 to the National Building Code of Canada for an excellent account of the restivity to fire of a wide range of combinations of building materials.

SECTION 11

FIRE EFFECTS ON WOODLANDS AND EDIBLE CROPS

11.1 In a nuclear attack, there is a risk that valuable stands of forests, growing grain crops and fodder may be destroyed by fires that have been started by ignitions occurring beyond the boundaries of a target city. However, it is not meant to imply that the losses may be greater than those incurred in peace-time fires, but rather, that they may be relatively more onerous when coupled with the damage sustained by industry in target cities. Nevertheless, it is by no means certain that serious fires will be caused in woodlands or crops due to radiant heat emission. For this reason, it may be valuable to discuss briefly the conditions necessary for the promotion of extensive fires in forests and grass crops.

11.2 Forest Fires - Forest fire losses are governed by the extent of the stand in which a fire has occurred and by the type of trees which it contains. Generally, forests of needle-bearing trees such as pine, fir and hemlock, tend to suffer greater damage than stands of broad-leafed trees such as birch and oak. This is not only due to the properties of the trees themselves, but also to the fact that needle-bearing tree forests are often much more extensive than those of broad-leafed trees. In either case, fires are usually associated with the tinder materials existing on the forest floor. This comprises underbrush and dead organic matter such as leaves or needles and twigs that have dropped from nearby trees and accumulated over a considerable period of time. When this material is dry it is often prone to ignite readily, and flame-spread in the more or less finely divided tinder may be quite rapid. When its moisture content is high, ignition becomes more difficult to achieve and natural flame spread may be slow or even impossible. Less frequently, fires may advance through the crown foliage of the forest but, in the main, living foliage does not burn as well as the dried, dead material that may exist on the ground. Nevertheless, crown fires often occur as a result of blazes on the forest floor. When this happens there is a danger of flying brands being propelled by winds to ignite further fuels well in the van of the advancing fire. The effect of fire on living trees of more than a few inches diameter is usually to char the trunks to a depth of a half an inch or so and, often if the damage is extensive, to kill the trees. While the wood inside the charred surface may be unscarred and useable, it is necessary to recover it soon after the fire before decay is advanced. However, the more serious results usually stem from the loss of growth of trees that have not achieved maturity.

11.3 As forest fires depend mainly on the material existing on the floor of the forest, the risk of a blaze is, to some degree, predictable from its proneness to ignite. Tables that provide a qualitative measure of the risk are produced by the Department of Forestry of the Federal Government of Canada. In general, the danger is low in the presence of a snow cover and in rainy weather. However, in a period of drought the danger increases. When coupled with a conditon of low relative humidity, and in the presence of a drying wind that may also serve to drive a fire through woodlands, the risk of fire may become very great. This is particularly true in extensive needle-bearing tree forests where the tinders usually burn well and where drying is often accelerated by a lack of shade at the ground due to sparse crown foliage. The danger to broad-leafed tree forests tends to be rather less. This is attributable to the fact that the dead leaves do not usually burn quite as readily as needles and that, often, the ground tinder is well shaded from the drying effects of the sun. Furthermore, stands of broad-leafed trees tend to be more limited in extent than stands of needle-bearing trees so that losses may be correspondingly less.

11.4 It may be concluded that the risks to forests in a nuclear attack are strongly dependent on the type of trees that they contain and upon the weather conditions that precede an attack. Naturally, they also depend on the thermal emission characteristics of the weapon (see Figure 7.16.2) and atmospheric attenuation (see Figure 4.10.1). As the shade at ground level is likely to be incomplete in any forest, it is safe to assume the values of τ_B and τ_W to be unity in Equations 5.12.1, 5.12.2 and 5.12.3.

11.5 Fires in Edible Crops - In much the same way that the risk of forest fires resulting from a nuclear attack is dependent on weather and the energy of the weapon, so also is the danger to crops and grasses on range land. As a general rule, the ease of ignition depends on water content which is governed largely by seasons and climate. In Western Canada the risk of fire in standing cereal grain crops, such as wheat, oats and barley, is greatest in the period from harvest time to the onset of winter. From seeding time to harvest time the danger is usually quite small. Similarly, grasses in range land are prone to ignite in the period between July and winter. At other times, the risk is much reduced or even non-existent. In Eastern Canada, the fire risk in stubble fields is appreciable only in a short season that appears to be confined to August and September, while lightly grazed land may be regarded as providing poor fuel except possibly during very short periods in the spring and fall. It is rare that an extensive fire will occur while grain crops are bearing fruit. The higher risks usually coincide with periods following harvests when the ears have been removed and the stover remains.

11.6 If crops are ignited and rapid fire spread occurs, the losses in the prairie provinces are likely to exceed those that may result in Eastern Canadian provinces. This is due to the generally greater extent of cultivated areas between substantial fire breaks in the former. Nevertheless, prior to harvest time the damage is likely to be confined to areas scorched by the radiant heat emitted from nuclear weapons. After harvest time, a great deal of animal fodder may be lost due to flame-spread in stover. However, the loss is confined to one year's growth while that of young trees in forest fires may take many years to replace. In this respect, agricultural losses may be the easier to sustain.

11.7 From these remarks it may be concluded that a deliberate attempt to set fire to woodlands and crops, by means of a nuclear weapon, requires that a great deal of careful attention be given to weather conditions and seasons. However, the resulting losses may be no greater than those suffered in peacetime fires.

SECTION 12

MINIMIZING FIRE LOSSES IN A NUCLEAR ATTACK

12.1 Whether in peace or in war, the principles of reducing losses due to fires do not vary. These principles are divisible into two groups. The first comprises the prevention of fires by the removal of unnecessary hazards. This may be regarded as passive defence. The second includes the provisions made for fighting fires that have been started. This may be termed active defence. Due to the probability of many fires being caused in a nuclear attack, some special consideration must be given to both forms of defence.

12.2 In matters of active defence, it is customary to rely heavily on the skill and experience of local fire services. However, it is well to realize that the regular service is usually limited in equipment, manpower and water-supply. Normally, these are sufficient to deal with peacetime conditions, but they are unlikely to be anything like adequate to cope with the very large number of fires which may be caused in a nuclear attack. Quite apart from this, there is always a risk that water mains service may be disrupted and efficient fire-fighting may become impossible. Furthermore, if a heavy deposit of local fallout should occur, the physical hazards from residual radiation may preclude fire-fighting of substantial fires for a considerable period of time. Thus, it is a matter of good judgment in deciding where regular fire servicemen may best be employed. Obviously, there is little virtue in attempting to fight all blazes when resources are dispersed too thinly to be effective. In general, it would seem that the better plan would be to attempt to choose areas where the highest reward for the effort expended is most likely to accrue and where a water supply is reasonably assured. The likelihood is that these would occur near the fringes of the primary ignition zones. However, if dangerous amounts of local fallout are deposited, efforts may have to be confined to districts where the hazards to personnel are acceptable.

12.3 These restrictions on the use of the regular fire service infer that the main burden of extinguishing blazes would fall on the occupants of buildings. During World War II, a large measure of reliance was placed on the civil population of many European cities to combat small fires before they grew beyond unskilled control. The results appear to show that the confidence was not misplaced and that many small fires, when dealt with promptly, may be extinguished without great trouble and with a minimum of loss. In a nuclear war, it is almost imperative that people are able to perform these duties in the limited time between detonation and the possible arrival of heavy local fallout, and with the knowledge that they may not be assisted by highly

trained fire servicemen. This calls for a certain amount of self-control that is not possessed by all. The more certain approach is that a great number of people are trained in the rudiments of simple fire-fighting in such a manner that their training may surmount some of the human frailties in a time of stress, so that they are likely to respond quickly to the danger of fire spread.

12.4 Many large buildings are equipped with defensive equipment to combat fires. Some have water-sprinklers, fire-shutters, hand-extinguishers and hose-reels; others rely on sand and water buckets. Bearing in mind that water supplies or the supply of electricity to pumps may fail, it would seem that the most certain equipment to rely upon in a nuclear attack is hand-operated gear. While it cannot be suggested that buckets of water and sand or hand extinguishers may be effective near ground zero to combat fires, it is very likely that as the boundary of the probable primary ignition zone is approached these simple devices may be very valuable indeed. The reason is that the occurrence of fires depends on the existence of fewer and fewer varieties of tinders as distance from ground zero increases. Correspondingly, the number of ignition points tends to diminish and the ability to combat small blazes successfully is enhanced. This being the case, it is a remarkably cheap insurance to provide water, sand buckets or sand bags that may mean the difference between substantial and minor loss. It should not be thought that the more elaborate sprinkler or hose systems are valueless. On the contrary, provided that water is available and that pumps will work, they may be expected to perform a much better service than the simpler systems. However, as pointed out above, in a nuclear attack condition there is always some risk of disruption of public services that may preclude their use.

12.5 There have been some attempts to provide a method of minimizing expected fire losses by other than conventional means. One suggested approach has been to insert a thick pall of artificially-produced smoke between detonation point and target. The reasoning is that the smoke particles may diffuse and absorb radiant heat and thereby reduce the amount delivered to the target. This is analogous to the effect produced by changes of visibility (see, for example, Table 7.22.1) on the size of the primary ignition zone. Unfortunately, a number of practical difficulties are encountered. The more obvious of these are the production of an amount of smoke sufficient to cover the target area adequately in the interval between the warning and launching of an attack, and the ability of the smoke cloud to remain in position without being blown away by winds. Naturally, these difficulties lessen as the target area diminishes, but, for larger cities, they are very great.

12.6 Passive defence against peacetime fires is conducted in several ways. Probably the most obvious of these is the legislation that requires buildings to be constructed of fire resisting materials

and to be separated in a manner that will retard the onset of conflagration. It has been pointed out (see Section 8.9) that existing building laws are presumably based on the economic use of land,that does not always permit a separation between buildings which will afford a great measure of safety against the risk of fire-spread. To some extent, the same reasoning applies to construction materials. From this it would appear that, in peacetime, the prompt attendance of the fire service is assumed to be available to control blazes. Due to the circumstances that may prevail during a nuclear attack, the assumption may not be valid in time of war. Therefore, this form of passive defence may be assumed to be of limited value in densely populated areas.

12.7 The fire service has looked upon good housekeeping as fundamental to fireprotection in peacetime. In wartime it takes on a much greater significance. It is fair to assume that the risk of ignition depends on the number as well as on the type of tinders that are available. Therefore, it may be concluded that, when unnecesary tinders are removed and disposed safely, there is some assurance that, if a nuclear attack should develop, the number of small blazes to be fought is a minimum. In the same sense, it is important to emphasize the benefits of incombustible or fire-retardant treated fabrics that lessen the risk of a rapid fire-spread. Indeed, with thought and care it is conceivable that these simple passive defence measures may significantly diminish fire losses in a nuclear war.

12.8 From these general remarks it may be concluded that simple and cheap active and passive defence measures, taken by building tenants, are likely to be most useful in reducing fire losses. The fact that fire damage following a nuclear attack is likely to be enormous cannot be denied, but it is good sense to take precautions that may do much to diminish the losses and save lives.

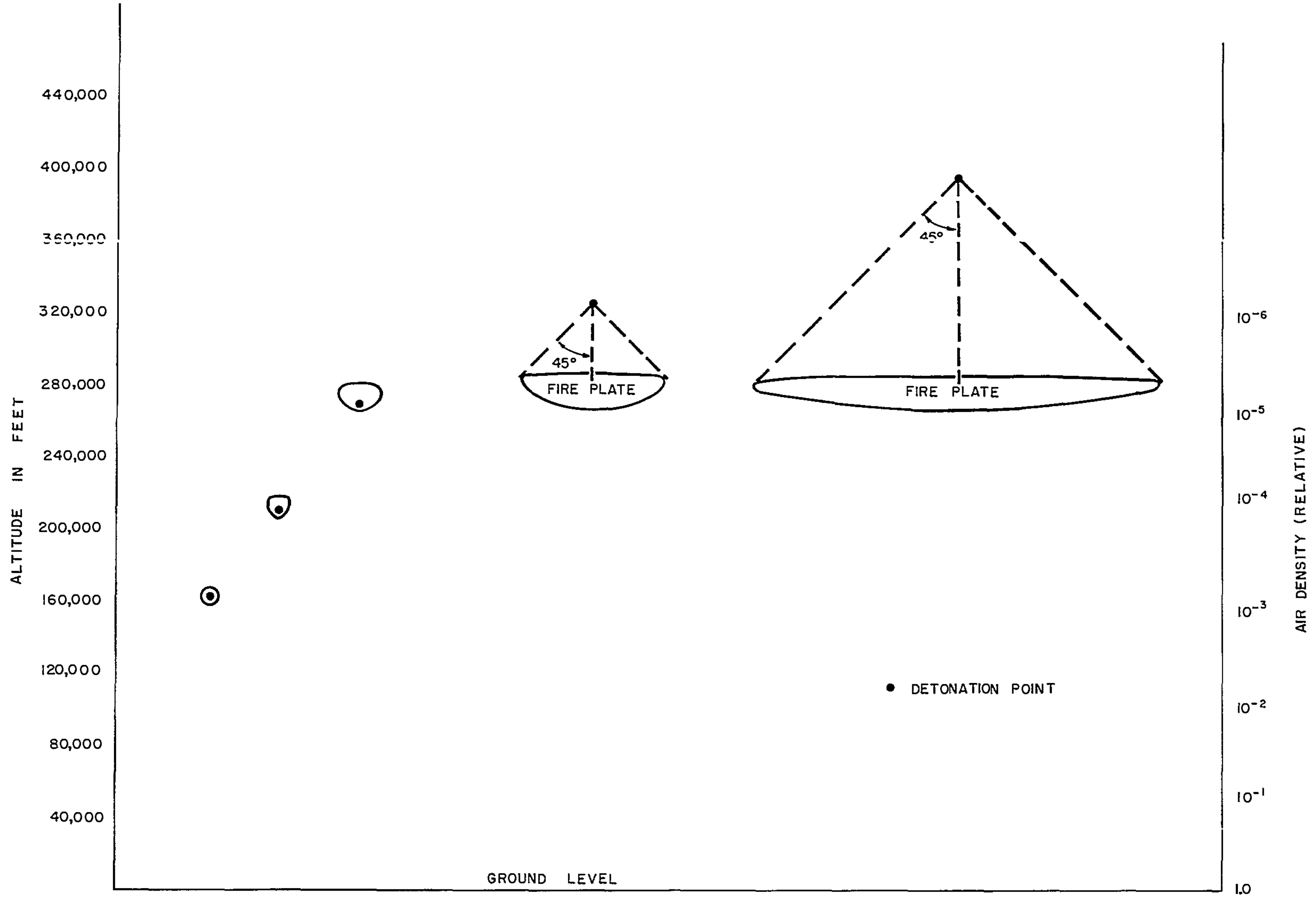


FIG. A.4.1. THE APPROXIMATE SHAPE AND LOCATION OF THE FIREBALL FOR VERY HIGH YIELD NUCLEAR DETONATIONS AT FIVE ARBITRARILY SELECTED ALTITUDES.

APPENDIX A

THERMAL EMISSION FROM HIGH ALTITUDE WEAPONS

A.1 In Section 3.4, a distinction was made between nuclear weapons detonated below an altitude of 100,000 feet and those detonated at greater heights. Sections 3, 4 and 5 were devoted to a discussion of the former; this appendix deals with the latter. There are two reasons for separating the discussions. The first is that the thermal emission characteristics are markedly different, thus making a separation convenient. The second is that data are lacking on high-altitude bursts and their discussion is, necessarly, more qualitative in character.

A.2 There is not a great deal of information available on the effects of weapons detonated between altitudes of 100,000 feet and 150,000 feet. However, predictions of the character and delivery of heat from weapons detonated above 150,000 are available and attention must be confined to this case.

A.3 It may be recalled from the account given in Section 3, that a fireball is created by the delivery of energy from X-rays emitted from a detonating weapon to the surrounding atmospheric gases. These are rendered into an incandescent state and heat is re-radiated from the surface of the resulting heated space, which acts, more or less, as a black-body radiator. Part of this heat may impinge on inflammable targets and ignite them. In exactly the same manner, high-altitude detonations cause an energizing of molecules and atoms of atmospheric gases. But, due to the greatly decreased air density present at high altitudes, the probability of X-rays impinging on molecular or atomic particles near the detonation point is correspondingly lessened. Therefore, the distance through which inter-action occurs is much greater than those associated with weapons detonated at low altitudes. This results in the creation of large fireballs, often several miles in diameter, from whose surfaces heat may be re-radiated. It may be concluded that the target coverage, or, termed otherwise, the potential zone of primary ignitions, tends to be more extensive than that due to a low-altitude weapon of comparable energy.

A.4 This increase of fireball size would appear to imply that more thermal damage is likely to result as the altitude of the detonation point is increased. However, the argument is of limited validity. Above an altitude of approximately 280,000 feet the atmosphere is so rare that it is substantially non-existent. Therefore, in the absence of atmospheric gases, no fireball is created above this height. This produces a rather curious effect. If it is supposed that a weapon is detonated at, say, 350,000 feet, most of the X-rays are discharged into the

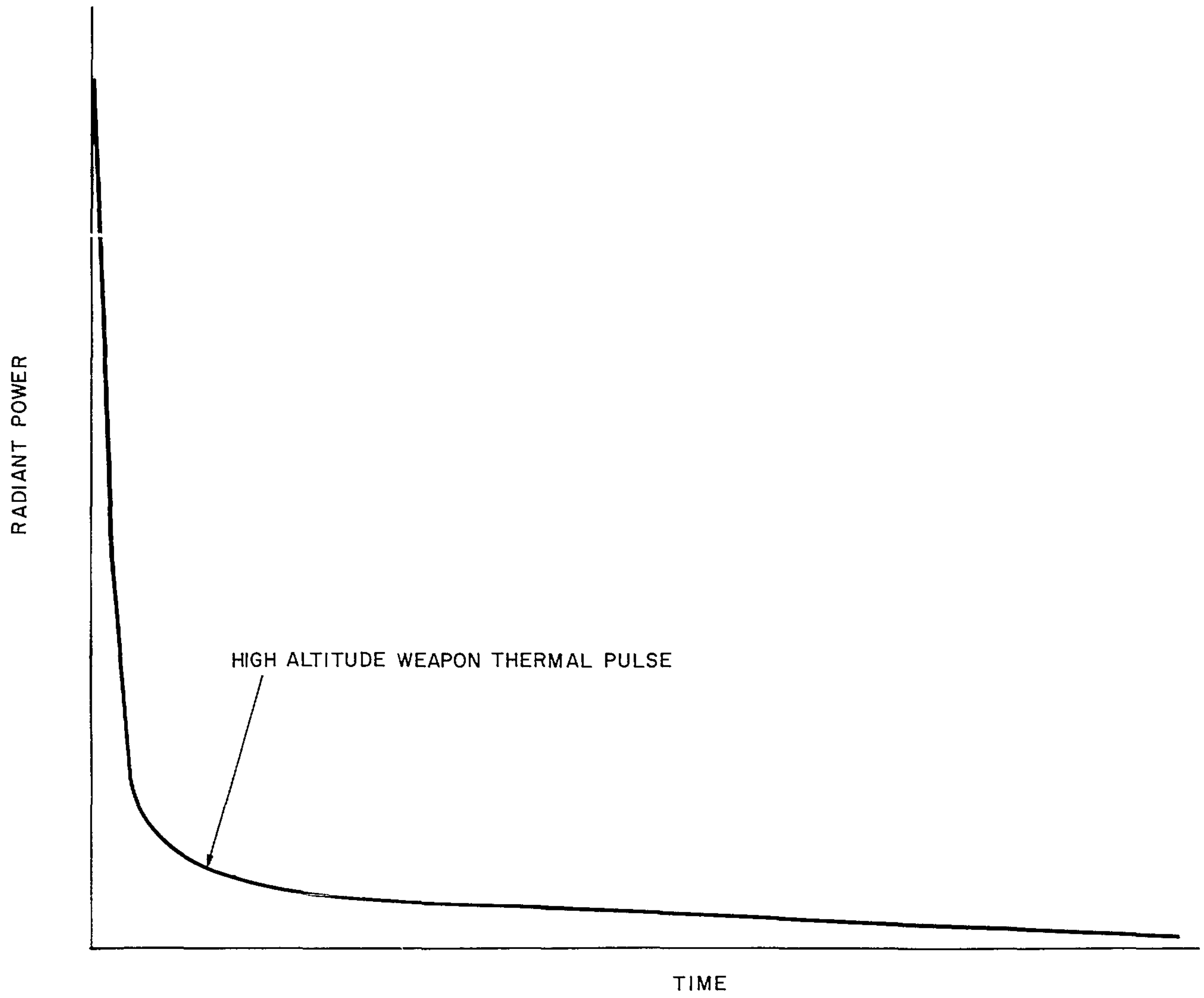


FIG. A.5.1 DIAGRAMMATIC POWER-TIME RELATIONSHIP FOR HIGH-ALTITUDE WEAPON DETONATION

stratosphere where their effect is harmless as far as the creation of fires is concerned. However, a portion of the discharge is directed downwards to the upper atmosphere where it interacts with the available gases and excites them. Instead of producing a fireball around the detonation point, a fire-pancake or fire-disc, shaped rather like a truncated sphere, forms below the detonation point in layers of upper atmospheric air. Fireball shapes resulting from weapons detonated at varying high altitudes are shown diagrammatically in Figure A.4.1.

A.5 It may be recalled from Section 3.5 that, in the case of low-altitude bursts, the fireball was shadowed during an early part of its growth by a shock front that advanced before it. This results in the apparent delivery of two pulses of re-radiated heat. In high-altitude bursts, low air density prevents the early formation of a powerful shock front with the result that a considerable portion of the available heat is delivered before shock has any significant attenuating effect. Thus, in effect, only one heat pulse is promoted and this takes a form shown diagrammatically in Figure A.5.1. It is obvious from this figure that the power immediately after detonation, is very high and that it decreases sharply as time progresses. The shape of the curve suggests equations of the form $P = Ae^{-Bt}$ or $P = At^{-B}$, where P = thermal power in calories per square centimetre per second, t = time in seconds, and A and B are pure numbers. Miller and Passell[21] show that the power delivery curve does not follow a single power-time relationship, but, more closely follows a relationship of the form $P \propto t^{-x}$, where x is variable and dependent on detonation altitude, during the period from detonation until the fireball temperature decreases to approximately $10^4\,^{\circ}K$. Subsequently, the relationship appears to be given approximately by $P \propto t^{-1.29}$. All of these expressions require that the power is infinite at zero time. Obviously, this cannot be true. Rogers[22] suggests that the characteristic form of the energy pulse may be roughly approximated by the second, major, pulse of a 500 to 700 kiloton total energy yield weapon detonated near ground level.

A.6 Another approach, which, however, cannot be substantiated, is to note from Section 3.6 (see Figure 3.7.1) that the observed fireball surface temperature of a weapon detonated near the ground is quite different from its true temperature. It seems possible that a similar effect may be experienced with high-altitude weapons. If, for the sake of argument, it may be assumed that the apparent temperature peak occurs at approximately $10^4\,^{\circ}C$ for all weapons, of any energy and detonated at any high altitude, at 4×10^{-4} seconds after detonation, then it is possible to make an estimate of power delivery provided that the corresponding energy received is known. On this basis, let it be assumed that the delivered power varies with time in accordance with the curve, shown diagrammatically in Figure A.6.1 where the power rises linearly to a peak occurring at 4×10^{-4} seconds and decays in

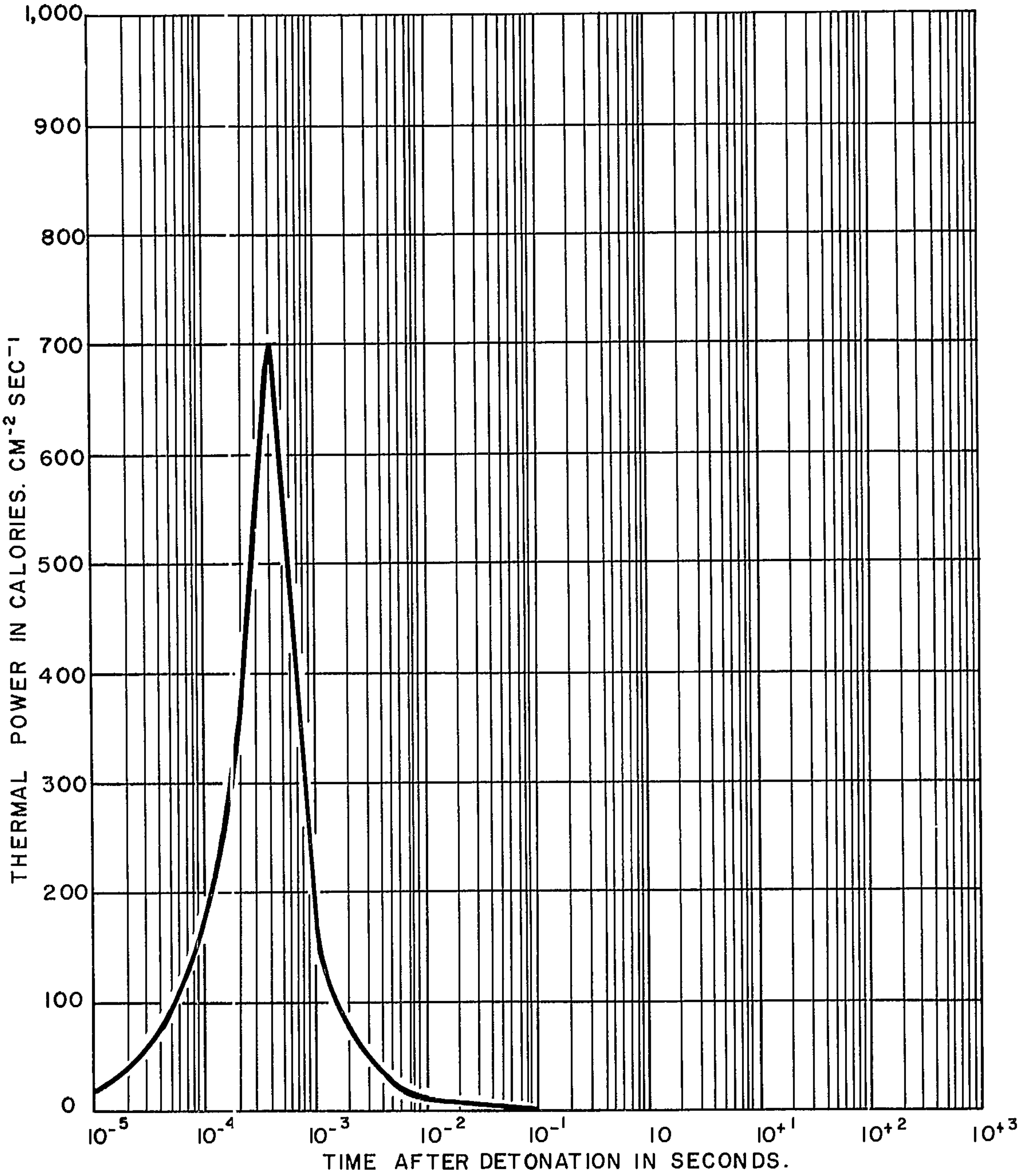


FIG. A.6.1. ASSUMED POWER-TIME VARIATION OF THERMAL EMISSION OF HIGH-ALTITUDE WEAPON DELIVERING 1 CALORIE PER SQUARE CENTIMETRE IN 1 SECOND AFTER DETONATION. (SEE SECTION A.6. FOR EXPLANATION).

accordance with the law $P = (4.14 \times 10^{-5}) \; P_p t^{-1.29}$, where P = power at any time, t, in seconds, after peak power, P_p, has been attained. If the energy delivered in, say, 1 second after detonation is known, then the relationship given in Equation A.6.1 may be formulated. This may be shown to produce the result given in Equation A.6.2. If, for example, it is assumed that Q_1 = 1 calorie per square centimetre, it may be deduced that P_p = 696 calories per square centimetre per second.

$$Q_1 = 2 \times 10^{-4} \; P_p + (4.14 \times 10^{-5}) P_p \int_{4 \times 10^{-4}}^{1.0} t^{-1.29} dt \qquad - \text{A.6.1}$$

where Q_1 = total energy delivered in 1 second after detonation

$$Q_1 = 1.436 \times 10^{-3} \, P_p \qquad - \text{A.6.2}$$

While it cannot be suggested that the approach truly represents the power delivery mode of a high-altitude weapon, it does have the advantage of avoiding the obviously bad assumption that maximum power approaches infinity at zero time after detonation.

A.7 Miller and Passell[21] show that the amount of energy delivered as heat capable of producing fires through a transparent atmosphere (i.e. where no scattering or reflected losses occur) lies in the range of 25 to 35 percent of the total weapon energy yield. This range is valid for altitudes of detonation between, approximately 150,000 and 260,000 feet. For these conditions, they produced two sets of curves that are shown, in part, in Figures A.7.1 and A.7.2. The former shows the total heat delivered at ground zero for a wide range of weapon energies and altitudes; the latter shows the diminution of thermal energy delivery as horizontal distance from ground zero increases.

A.8 Passel[23] qualified his study of heat delivered from high-altitude weapon to include more realistic atmospheric losses. This was accomplished by comparing the weapon's emission with the luminous energy of the sun arriving at ground level normal to the sun's rays. While this is not strictly correct, it does provide some measure of the heat losses in the atmosphere. The results of his findings are shown, in part, in Figure A.8.1, where the fraction of the extra-terrestrial radiation delivered through a transparent atmosphere to a surface normal to the direct rays is plotted against the angle of elevation above the horizontal to the centre of the fireball (or fire-pancake). It may be seen from this figure that approximately 80% of the thermal delivery given in Figure

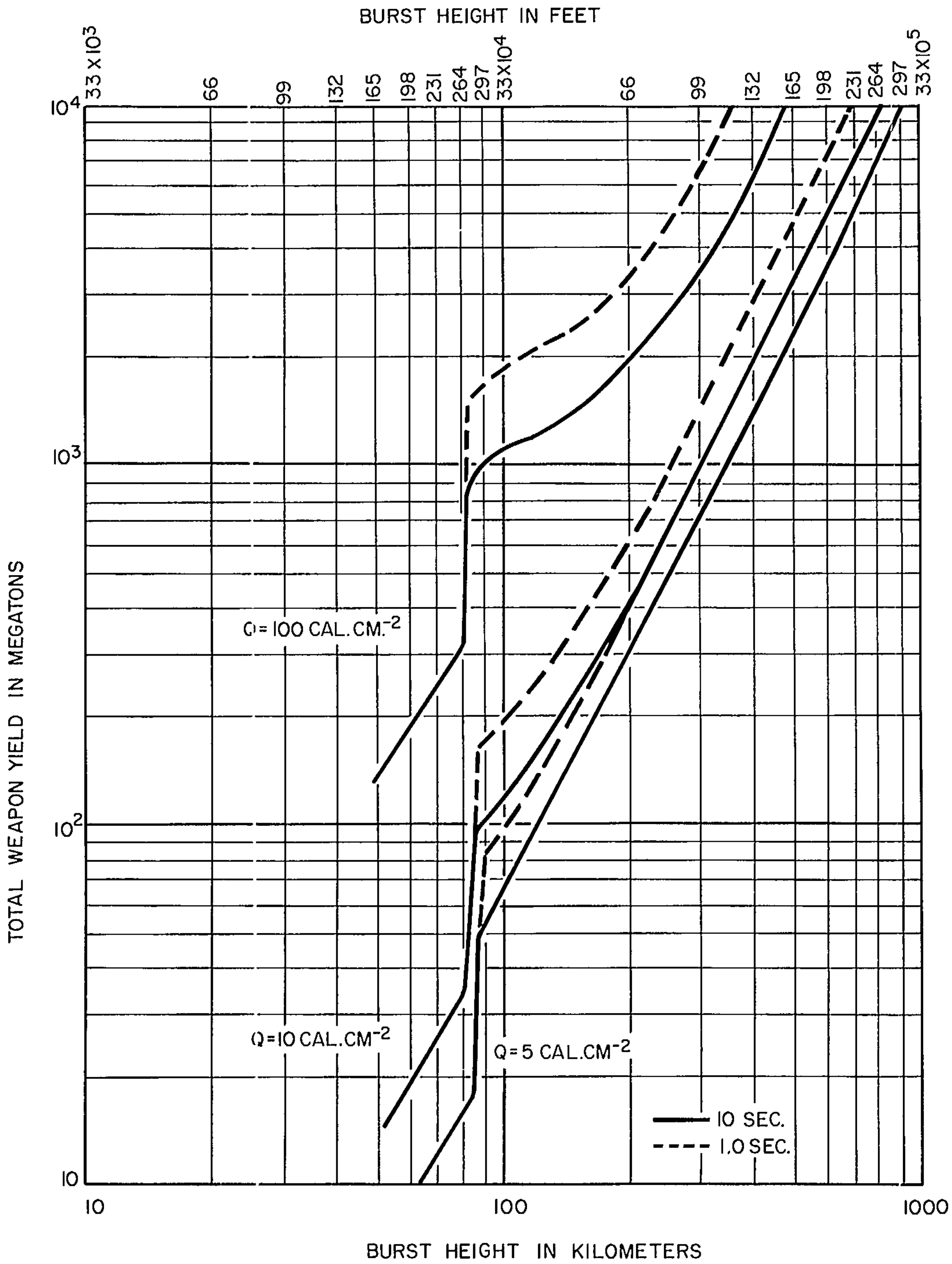


FIG. A.7.1. THE TOTAL WEAPON YIELD REQUIRED AT A GIVEN BURST HEIGHT FOR THREE ENERGY FLUXES DELIVERED TO A HORIZONTAL SURFACE AT GROUND ZERO WITHIN 1 AND 10 SEC. AFTER DETONATION.

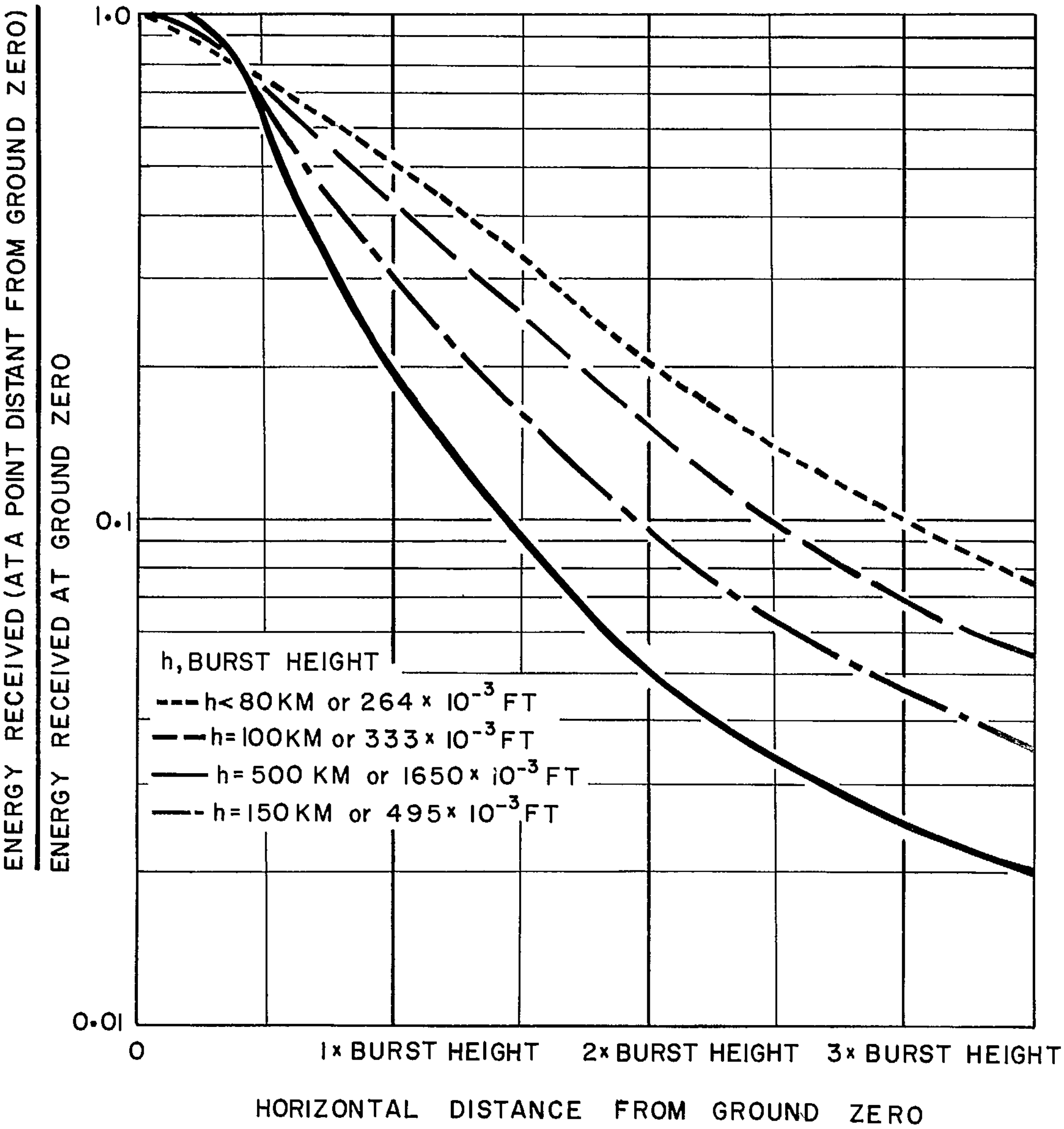


FIG. A.7.2. ENERGY FLUX RECEIVED IN OPTIMALLY ORIENTED SURFACES AS A FUNCTION OF DISTANCE FROM GROUND ZERO.

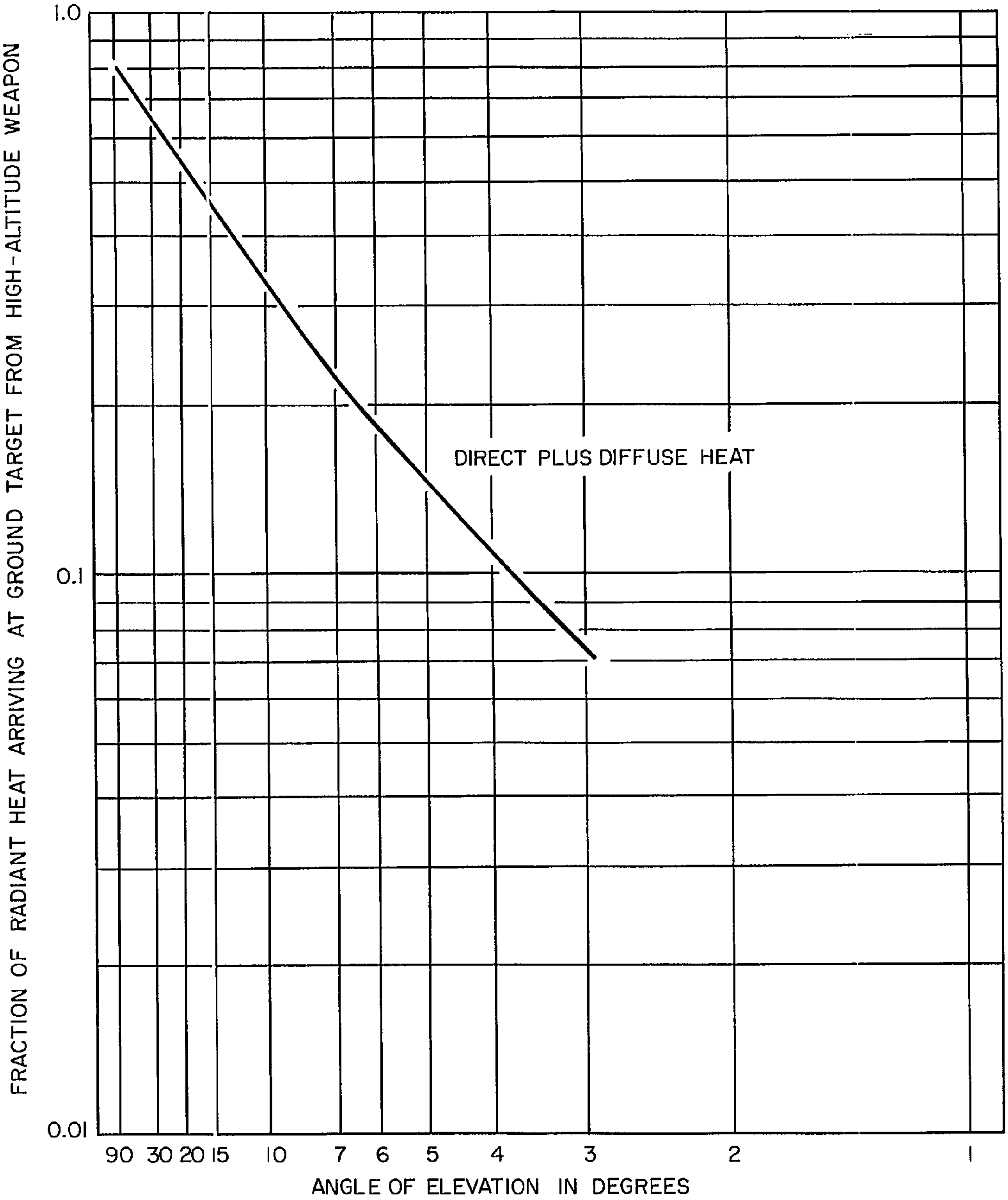


FIG. A.8.1 ATMOSPHERIC ATTENUATION FACTORS FOR HIGH-ALTITUDE NUCLEAR DETONATIONS AS A FUNCTION OF ELEVATION ANGLE OF THE RAY ABOVE HORIZONTAL FOR AVERAGE CLEAR DAY AT SEA LEVEL. (ADAPTED FROM "TRANSMISSION OF THE EARTH'S ATMOSPHERE OF THERMAL ENERGY FROM NUCLEAR DETONATIONS ABOVE 50 KM ALTITUDE" BY T. O. PASSELL)

A.7.1, is available at ground zero. However, this does not include the effect of the presence of clouds which predominantly occur well below the lower elevation limit of 150,000 feet with which this discussion is concerned. Passell[23] has attempted to relate the transmission of heat with cloud thickness and cloud cover. His relationship is shown, in part, in Figure A.8.2. It should be noted that the curve is a plot of transmission to sea level relative to a clear day, against cloud thickness. This means that a value of delivered heat taken from Figure A.7.1 must be multiplied by corresponding coefficients taken from Figures A.7.2, A.8.1 and A.8.2 to attain a reasonably accurate estimate of the heat delivered at any point in the target area. This may be illustrated by a simple example.

Example It is assumed that a 20 megaton total energy yield weapon is detonated at an altitude of 280,000 feet.

It is required to find the heat delivered at ground zero on

(a) A day of light haze
(b) A day of heavy cloud

Solution From Figure A.7.1

Thermal delivery = 5 calories. cm^{-2}

From Figure A.7.2.

$$\frac{\text{Energy received at a point distant from ground zero}}{\text{Energy received at ground zero}} = 1.0$$

From Figure A. 8. 1

Fraction of extra-terrestrial radiation arriving at ground surface (elevation = 90°) = 0.8

From Figure A.8.2

Transmission by cloud relative to clear day for light haze = 0.7 approx.

From Figure A.8.2

Transmission by cloud relative to clear day for heavy cloud = 0.1 approx.

FREQUENCY OF OCCURRENCE OF CLOUD COVER, IN TENTHS AS PERCENTAGE OF TOTAL TIME IN ONE CALENDAR MONTH

	VANCOUVER, B.C.			EDMONTON, ALTA.			WINNIPEG, MAN.			TORONTO, ONT.			MONTREAL, QUE.			HALIFAX, N.S.		
	0-4 Tenths	5-9 Tenths	10 Tenths	0-4 Tenths	5-9 Tenths	10 Tenths	0-4 Tenths	5-9 Tenths	10 Tenths	0-4 Tenths	5-9 Tenths	10 Tenths	0-4 Tenths	5-9 Tenths	10 Tenths	0-4 Tenths	5-9 Tenths	10 Tenths
January	14.8	26.3	58.9	33.7	31.4	34.9	40.4	21.9	37.7	28.6	24.3	47.1	32.7	24.6	42.7	30.5	23.0	46.5
February	19.6	31.6	48.8	32.4	34.6	33.0	46.2	20.4	33.4	29.7	24.8	45.5	34.2	24.3	41.5	35.3	22.5	42.2
March	22.0	38.7	39.3	31.0	33.5	35.5	39.8	26.2	34.0	37.5	24.0	38.5	38.2	26.8	35.0	32.5	26.6	40.9
April	26.1	41.7	32.2	33.6	42.2	24.2	36.6	31.3	32.1	33.7	28.6	37.7	33.8	30.1	36.1	32.5	24.6	42.9
May	31.8	43.1	25.1	31.3	46.3	22.4	38.1	32.2	29.7	38.3	33.7	28.0	36.4	38.1	25.5	32.4	28.2	39.4
June	27.4	47.2	25.4	29.2	51.7	19.1	36.2	41.4	22.4	43.0	37.4	19.6	38.1	38.9	23.0	28.2	29.6	42.2
July	54.0	35.0	11.0	39.9	49.7	10.4	45.9	40.8	13.3	49.1	38.2	12.7	40.0	43.3	16.7	33.7	29.8	36.5
August	43.4	38.1	18.5	37.8	44.1	18.1	47.4	37.2	15.4	47.9	34.8	17.3	44.7	38.8	16.5	36.1	30.9	33.0
September	39.4	34.6	26.0	35.3	45.2	19.5	37.9	38.5	23.6	46.2	33.7	20.1	40.7	35.0	24.3	40.9	29.4	29.7
October	23.3	36.8	39.9	35.5	41.8	22.7	39.7	30.6	29.7	42.1	30.9	27.0	37.7	31.0	31.3	39.0	26.1	34.9
November	19.0	31.0	50.0	37.9	33.7	28.4	25.9	25.5	48.6	26.6	32.9	40.5	24.1	32.0	43.9	28.2	25.1	46.7
December	14.8	31.6	53.6	32.0	37.4	30.6	34.3	24.5	41.2	26.5	26.1	47.4	27.8	25.9	46.3	28.4	27.5	44.1

TABLE A.8.1 - INCIDENCE OF CLOUD COVER OVER SELECTED CANADIAN CITIES EXPRESSED AS A PERCENTAGE OF TIME IN ONE CALENDAR MONTH. ADAPTED FROM OBSERVATIONS MADE OVER A TEN-YEAR PERIOD (JAN. 1953 - DEC. 1962) BY THE METEOROLOGICAL BRANCH OF THE DEPARTMENT OF TRANSPORT, GOVERNMENT OF CANADA.

(a) Heat received on day of light haze $= 5.0 \times 1.0 \times 0.8 \times 0.7$ calories . cm^{-2}

$= 2.8$ calories. cm^{-2}

(b) Heat received on day of heavy cloud $= 5.0 \times 1.0 \times 0.8 \times 0.1$ calories . cm^{-2}

$= 0.4$ calories. cm^{-2}

Answer

It is readily seen from the example that cloud cover has an important effect in attenuating heat. However, the data in Figure A.8.2 refer to a more or less unbroken cover. It is interesting to compare the occurrence of cloud in selected Canadian cities with the conditions assumed by Passell. The data presented in Table A.8.1 are a record of the visual observations made by Department of Transport observers, near the cities indicated, over a ten year period from 1953 to 1962. The figures are estimates of the amount, in tenths, of sky obscured from the observer's view by cloud. Obviously, if the cover is broken the delivery of heat will depend on the distribution of clouds. To make some allowance for this, it is probably easiest to interpolate between the no-cover and complete-cover conditions at some assumed figure of, say, five-tenths obscurity or at any other chosen value.

A.9 It may be noticed that the attenuating effects of exterior and interior shielding and those of glazing and window screen have been omitted from the discussion of thermal delivery from high-altitude weapons. Obviously, as these may produce a marked reduction in the amount of heat delivered to tinders located indoors, their presence should not be neglected. Due allowance may be made using the principles described in Section 5.

A.10 Figure A.7.1 shows that the energy per unit area delivered to ground targets from high-altitude weapons of relatively high energy yields is not very large. However, it has been indicated that the corresponding peak power is likely to be very large indeed. This poses the question of the manner in which ignition of a tinder is likely to occur. Some idea of the probable answer lies in the data presented in Figure 7.17.1. This may be demonstrated in the following way. Let it be assumed that the hypothesis given in Section A.6 is correct and that the total energy input is 1 calorie per square centimetre (it may be seen in Figure A.7.1, that, over a considerable range the energy delivered in 1 second does not differ greatly from that delivered in 10 seconds)

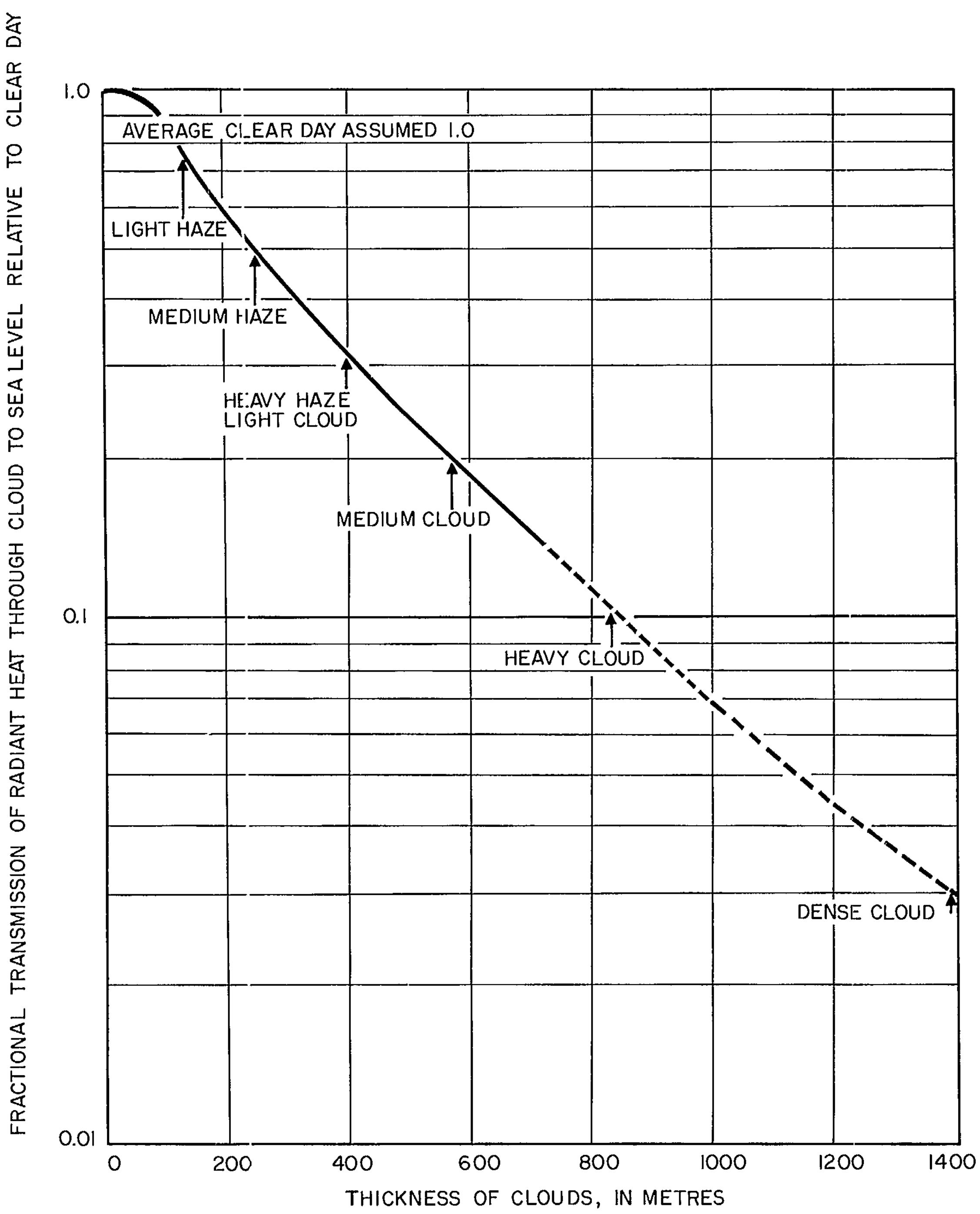


FIG. A.8.2. ATMOSPHERIC ATTENUATION FACTORS FOR HIGH ALTITUDE NUCLEAR DETONATIONS AS A FUNCTION OF CLOUD THICKNESS AND/OR DENSITY AS VISUALLY JUDGED. (ADAPTED FROM "TRANSMISSION BY THE EARTH'S ATMOSPHERE OF THERMAL ENERGY FROM NUCLEAR DETONATIONS ABOVE 50-KM ALTITUDE" BY T. O. PASSEL)

DESCRIPTION OF NEWSPAPER	POWER ($cals. cm^{-2}, sec^{-1}$)	ENERGY ($cals. cm^{-2}$)
Darkest Areas	50	2.1
	75	2.5
	100	2.8
Half-tone Areas	50	3.0
	75	3.0
	100	3.3
Text Areas	50	4.0
	75	4.5
	100	5.0
Unprinted Areas	50	5.5
	75	4.5
	100	5.5

Table A.11.1 THERMAL POWER AND ENERGY REQUIRED TO PRODUCE SUSTAINED FLAMING IGNITION OF NEWSPAPER. CONDITIONS OF HIGH POWER APPLIED BRIEFLY.

(ADAPTED FROM "IGNITION OF CELLULOSIC KINDLING FUELS BY VERY BRIEF RADIANT PULSES" by S. MARTIN)

and the peak power is 696 calories per square centimetre per second. Let it also be assumed that the target tinder is a matt, dark, paper, roughly corresponding to the printed area of a newspaper, with a density (ρ) of 0.75 grams per cubic centimetre, a specific heat capacity (c) of 0.35 calories per gram per degree centigrade, a thickness (L) of 0.0075 centimetres, and a thermal conductivity (K) of 2.30×10^{-4} in compatible units. The energy modulus, $Q/\rho cL$, is therefore 5.10×10^2 numerically and the power modulus, P_pL/K, is 2.27×10^4 numerically. Entering Figure 7.17.1 with these values it is apparent that transient flaming ignition results. This implies that although the tinder may emit flame, the flame is likely to disappear when the source of heat is removed (see Section 7.3).

A.11 This tentative assessment of the type of ignition that may occur due to high-altitude weapons is borne out by the experimental work of Martin[24] who applied radiant heat to specimen tinders using a carbon arc source and a paraboloidal mirror. Uniform intensities of as much as 100 calories per square centimetre per second were applied to target papers for periods of several hundredths of a second. It was found that transient flaming occurred almost immediately after heat was applied. This tended to make the onset of sustained flaming ignition rather difficult to determine as the material often ablated to the extent that nothing was left to burn. Martin's findings suggest that, unless there were other tinders in close proximity to ignite to sustained flaming by a pilot ignition process from the target paper, the probability of fire spread is rather limited. A part of the results of these experiments is reproduced in Table A.11.1. The figures are given for various sections of newspaper that have been irradiated to sustained flaming.

A.12 A high-altitude weapon is incapable of producing local fallout and its blast effect is not as great as that of a detonation produced near ground level. However, it has been suggested that it is a much more efficient fire weapon than a low-level nuclear device as it is capable of a more uniform and a wider-spread thermal distribution. Undoubtedly, this argument has some validity. Nevertheless, it has great disadvantages to a military planner. Firstly, the transient flaming ignition characteristics are not usually as certain to produce major fires as sustained flaming ignition. Secondly, the presence of cloud cover has a substantial attenuating effect that may considerably reduce the risk of fires occurring in a target. Thirdly, if simultaneous attacks were to be made on a number of targets, there is no assurance that all will be reasonably free of cloud when the attacks are launched. Taken overall, it would appear that, for the present, the high-altitude weapon does not guarantee the same damaging results that may be expected of the weapon detonated near the ground.

APPENDIX B

A SHORT GLOSSARY OF TERMS

B.1 Conflagration	Defined in this manual as the spread of fire from one building to other buildings. The spread may be limited to one structure or it may involve many buildings.
B.2 Fireball	A luminous sphere of hot atmospheric gases formed around the detonation point of a nuclear weapon.
B.3 Fire Storm	Defined as a stationary mass fire, generally involving a large urban area, in which flame-merging is well adavanced. It generates local, strong, winds that flow inwards towards the fire area. These serve to replenish the supply of oxygen for combustion but they also intensify the fires. However, they effectively confine any strong tendency for outwards fire spread.
B.4 Kiloton	The energy of a nuclear explosion which is equivalent to that produced by the explosion of 1,000 tons of T.N.T.
B.5 Mass Fires	Defined in this manual as a group of individual building fires in which partial or complete flame-merging has occurred.
B.6 Megaton	The energy of a nuclear explosion which is equivalent to that produced by the explosion of 1,000,000 tons of T.N.T.

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